TECHNICAL SPECIFICATION

# ISO/TS 20273

First edition
2017-08

# Guidelines on weld quality in relationship to fatigue strength

*Lignes directrices sur la qualité de la soudure en rapport à la résistance à la fatigue*



Reference number
ISO/TS 20273:2017(E)

# Contents

Page

# Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee IIW, *International Institute of Welding,* Commission XIII, *Fatigue of welded components and structures*.

Requests for official interpretations of any aspect of this document should be directed to the ISO Central Secretariat, who will forward them to the IIW Secretariat for an official response.



# Introduction

This document has been derived from the main results given in Reference [28] which was previously published as XIII-2510-13. It constitutes the considered judgment of experts on fatigue in welded joints assuming thicker plates in steel. For further or more detailed information, see Reference [28].

This document is applicable where fatigue assessment is assumed to be based on either the nominal stress approach or structural stress approach as defined by References [1] and [2]. More refined fatigue assessment methods based on notch stress concepts or fracture mechanics already included the ability to completely or partially account for weld geometric features and imperfections and are not specifically covered by this document.

It is assumed that the user has a working knowledge of the basics of fatigue and fracture mechanics. In some cases, working knowledge of finite element analysis is also needed. The recommendations and guidelines are considered to reflect the fatigue strength of the welded joint itself with a defined survival probability but without environmental effects. They are thus applicable to many industrial sectors. It is assumed that the user will apply good principals of limit state structural design. Appropriate partial safety factors for load and resistance are to be applied depending on the industry. This document does not define the partial safety factors for load or resistance to be used in fatigue assessment.

# Guidelines on weld quality in relationship to fatigue strength

## 1 Scope

This document provides guidance for setting appropriate weld quality requirements in relation to fatigue.

This document is applicable to fusion (arc and/or beam welding) welded steel plate-type structures having a thickness of >3 mm, which are subjected to cyclic loading.

Due to lack of experimental data for aluminium welds and ultra-high strength steels, the fatigue strength (or S-N) curves apply only to structural steel up to a maximum specified yield strength of 960 MPa.

The acceptance criteria in this document may be applied to higher strength steels, stainless steels and certain concepts to 5000 and 6000 series of aluminium alloys which are commonly used in welded structures. In the absence of relevant published data, it is recommended that this be quantified by special testing.

## 2 Normative references

There are no normative references in this document.

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

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

**3.1**
**cold lap**
micro lack of fusion
region of non-fused *overlap* (3.7) between the weld metal and base plate which results in an imperfection parallel to the base plate

**3.2**
**effective notch stress**
elastic notch stress calculated for a notch with a certain assumed notch radius

**3.3**
**improved welds**
welds for which the weld toe is treated after welding by a grinding, re-melting or peening operation

Note 1 to entry: IIW guidelines for select post-weld treatment methods have been published.

**3.4**
**inclusion**
**slag inclusion**
non-metallic material entrapped in molten metal during solidification

**3.5**
**high quality weld**
weld with a lower level of imperfections such that it has fatigue strength greater than that defined in the IIW guidelines and recommendations with respect to nominal stress, *hot spot stress* (3.9) or *effective notch stress* (3.2)

Note 1 to entry: The improvement in fatigue strength is normally two FAT classes.

Note 2 to entry: Used in some standards.

**3.6**
**normal quality weld**
weld for which the level of imperfections is such that it satisfies the fatigue strength requirement defined in the IIW guidelines and recommendations with respect to nominal stress, *hot spot stress* (3.9) or *effective notch stress* (3.2)

**3.7**
**overlap**
protrusion of weld metal beyond the weld toe or weld root

Note 1 to entry: An overlap may be fused or non-fused. A toe overlap without fusion between the weld metal and base plate is the same as a *cold lap* (3.1).

**3.8**
**porosity**
cavities or pores caused by gas entrapment in molten metal during solidification

**3.9**
**structural stress**
**geometric stress**
**hot spot stress**
stress in a component, resolved to take into account the effects of a structural discontinuity on the surface at a hot spot, consisting of membrane and shell bending stress components

**3.10**
**undercut**
unfilled groove along the fusion line between weld metal and base plate

## 4 Symbols and abbreviated terms

| Symbol | Designation |
|---|---|
| FAT | All fatigue resistance data at 2 million cycles. The FAT classes are given as characteristic values, which are assumed to represent a survival probability of at least 95 %, calculated from mean value on the basis of a two-sided 75 % tolerance limits of the mean. Other existing definitions as e.g. a survival probability of 95 % on the basis of 95 % one-side limit of the mean or means minus two standard deviations corresponding to a survival probability of 97,7 % are practically equal for engineering applications.<br>Levels are arranged in steps. |
| $k_m$ | stress magnification factor for misalignment |
| $N_f$ | cycles to failure |
| $\Delta S$ or $\Delta\sigma$ | nominal stress range, acting on a structure |
| $\Delta S_c$ or $\Delta\sigma_c$ | characteristic nominal (resistance) stress range in MPa (see FAT above), but is a continuous variable when FAT are given in steps |
| $I$ | weld penetration |
| $R$ | weld toe radius |
| $a_i$ | initial crack dimensions |
| $t$ | thickness of plate |

| Symbol | Designation |
|---|---|
| *e* or *m* | misalignment between plates |
| *u* | undercut at weld toe |
| *α* | angle of weld |
| *a* | throat size of weld |
| *s* | *s*-measure from plate surface to butt joint weld penetration |

# 5 Background

## 5.1 General

Typical fabricated structures may have hundreds or even thousands of meters of weld. Thus, many potential fatigue cracking locations are present which should be considered during design development and production. The challenge is to optimize a design so that the welds have sufficient fatigue strength and fabrication quality to withstand the loads during the economic life of the structure or piece of equipment. Quality systems for welds are described in so-called weld class systems, such as ISO 5817[12] or Reference [50]. In these systems, acceptance limits are given for different weld geometry features or imperfections. Based on these limits, a weld is associated with a quality level, e.g. B, C or D. Intuitively, a high quality level, B, is assumed to perform better during service than a weld with a C or D quality level. The problem with the existing weld quality systems is that they were initially developed as a measure of “good workmanship” with respect to fabrication, i.e. as a measure of the skill of the individual or machine performing the operation. As such, they have been incorporated into a number of training and education programs for welders and weld inspectors. However, numerous studies have shown that the link between the existing weld quality classes and fatigue performance is not consistent.[16][52][53] Some acceptance criteria for some weld features or imperfections are found to have little or no influence on fatigue strength. For features which do influence fatigue strength, the acceptance criteria between quality classes, do not result in uniform changes in the fatigue strength. Realizing that fatigue is highly affected by the local geometric features and imperfections of the weld, systems like ISO 5817 could have been a good tool for quality measures regarding fatigue.

Designers of welded structures, on the other hand, think of weld quality in terms of performance, often called “design for purpose”. In this realm, quality would mean that a weld is able to perform its required function during the economic life of the component or structure. The required function may be a major like resistance to fatigue failure, sufficient strength with respect to extreme loads, permeability or corrosion resistance or the required function could be a minor functional property like hardness, resistance to abrasion, visual appearance or surface finish. This way of thinking is consistent with modern design guidelines for structures which are based on limit state design considerations. One important feature of limit state design is the existence of clearly identified conditions or limits that constitute failure or feasibility for a structure. For a designer, any discussion of quality should relate the definition of weld quality with the limit state(s) that quantify failure. Fatigue strength is one of the most demanding limit state design criteria for welded structures.



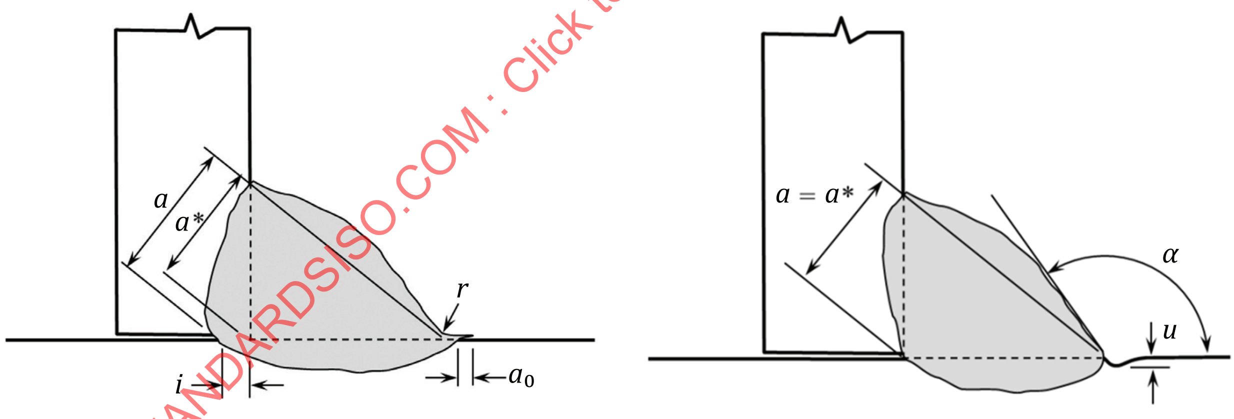
## 5.2 Design for purpose

The characteristic of the predominant load on the component is a major guiding consideration when formulating quality guidelines for load-carrying structures. For predominantly statically loaded welds, design calculations are based on the average stress in the weld net area. For this reason, ductility of the heat-affected zone (HAZ) and weld metal and sufficient weld throat thickness are the most important features. Imperfections like porosity, undercuts or cold laps have very little influence on the static capacity as long as the weld is ductile and the imperfections are small enough so as not to significantly reduce the weld cross-sectional area. Thus, ISO 5817 includes many acceptance criteria which are not relevant for static loaded joints. Throat thickness is by far the most significant geometric feature of a weld subjected to predominantly static loading. Weld type (butt, fillet, V-weld, K-weld), does not significantly influence strength for equal throat thickness.

Ductility and throat thickness are ensured by pre-production tests to validate the welding procedure specification (WPS). The same specification should ensure that crack-like imperfections are not formed during welding. For welded structures in high strength steel, matching or overmatching of the weld metal strength may be difficult to achieve. In this case, insufficient static strength of the filler material can be compensated by adding filler material. Loss of ductility, however, cannot always be compensated for by adding material so this is considered to be the most important basic requirement of welding. Joint ductility is assumed in all types of structural durability assessment. The WPS provides a guideline which ensures the deformation capacity and strength of the joint. Thus, when defining the welding parameters, it is important to prioritize those parameters that produce required quality. Following this, aspects which improve productivity can be considered. Some structures will naturally have only very low load carrying requirements and in these cases, optimization of production costs can bring significant savings for fabrication. One example of this type of weld may be, for example, long fixing welds in statically loaded structures.

For predominantly fatigue loaded structures, the demands of ductility and sufficient throat thickness are to be maintained. But, because fatigue strength is significantly influenced by the local characteristics of the joint, extra requirements with respect to weld geometry and imperfections are imposed. In addition to throat thickness and ductility, Reference [23], for example, identifies seven additional weld features which strongly influence fatigue strength: penetration, cold lap size, inner lack of fusion, weld toe transition radius, undercut size, joint misalignment and porosity (see Figure 1). It can be noted that in some technical literature, the cold lap imperfection in Figure 1 is sometimes referred to as a micro lack of fusion or a non-fused overlap. In technical literature, there is some inconsistency as to the definition of throat thickness, $a$, for partially penetrated welds. In this document, the definition is consistent with the Eurocodes, i.e. weld throat thickness also includes the penetration. The fillet size, $a^*$, is defined as being measured from the intersection of the plates as shown in Figure 1. Thus, for fillet welds with no penetration, $a = a^*$, and for fillet welds with penetration, $a$, approximately $a^* + i/\sqrt{2}$. Porosity is categorized based on pore location, diameter and whether the pores occur singly or as a cluster. Weld angle can have an influence on fatigue strength. However, for fillet welds with high fatigue strength, weld angle is less important than weld toe radius. For welds which have fatigue strength meeting IIW Recommendations, $\alpha \geq 120°$ is sufficient.






**Key**

$a$ throat thickness

$a^*$ fillet size

$a_0$ cold lap length

$\alpha$ weld angle

$i$ weld penetration

$r$ weld toe radius

$u$ depth of undercut

**Figure 1 — Fillet weld geometry features which significantly influence fatigue strength**

Root side fatigue can be the result of poor design or improper WPS. If a full penetration weld is not designated, lack of penetration may serve as a large initial defect. The greater defect, the shorter the expected life so the root side fatigue strength can vary from near zero to a value far exceeding the fatigue strength of the weld toe or plate edge. Designing against fatigue is thus strongly dependent on the weld penetration. The needed value of "*i*" is determined by analysis using the effective notch method, fracture mechanics or other suitable method. It is suggested that root side penetration should be specified on the production drawing and that the quality requirement is simply that penetration is equal to or greater than this value.

Based on the type of loading, differentiation is to be made between various joint categories. Design criteria and quality requirements will depend heavily on the primary function of the joint. Applied loads and structural geometry together establish the joint function. This is basically the essence of the concept called "Design for Purpose". The simple welded T-joints presented in Figure 2 can have numerous functions based on the applied forces, F1 to F4.

If the joint is loaded by the force component F1, the weld is a shear-loaded longitudinal weld. Web-to-flange welds in plate girders are typical examples of this type of weld. In such cases, the acceptance criteria related to the weld toe are rarely significant but failure from the weld root can occur.

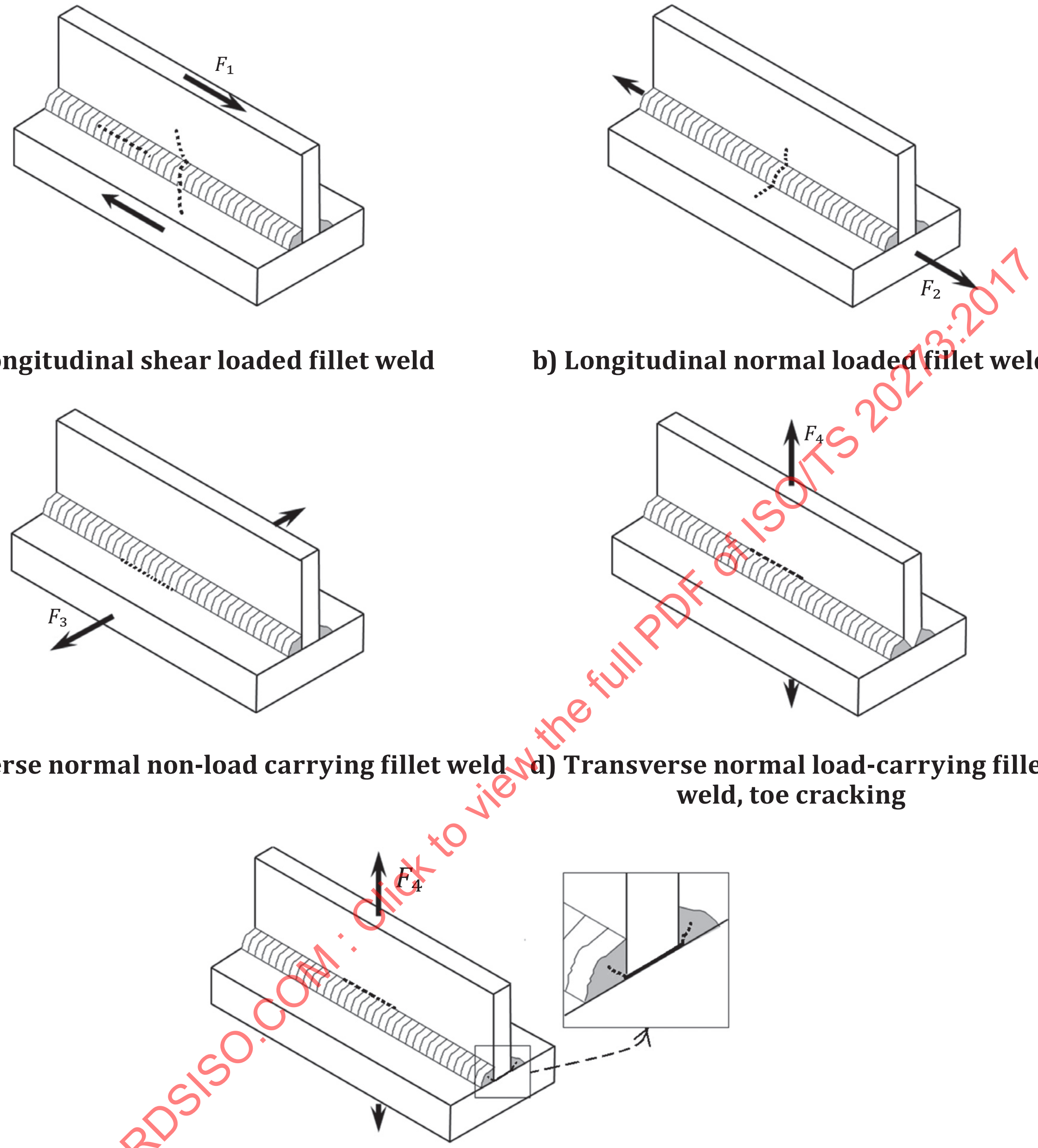
For the longitudinal weld loaded by F2, weld start and stop positions become critical and the waviness of the fusion line can have strong influence on fatigue strength. If the joint is loaded by the force component F3, the weld is a non-load carrying accessory weld and the weld toe geometry at the base plate to weld fusion line becomes crucial, i.e. by cold lap size, weld toe transition radius and undercut size. Welds loaded by F3 can also be considered as moderately demanding with respect to fabrication. A non-loaded accessory weld will never be critical in static loading cases but will often lead to fatigue failure.

For load-carrying fillet welds subjected to F4, the weld toe geometry at the attachment-to-weld fusion line is critical. Cold lap size, inner lack of fusion, weld toe transition radius, undercut size, joint misalignment porosity and weld penetration all potentially have strong influence on the fatigue strength of the joint. For a weld loaded with force F4, a root side fatigue crack can also develop depending on the degree of penetration. Welds loaded by F4 are the most demanding both with respect to design and fabrication because both the weld toe side and root side is to be considered.

## 5.3 Fatigue assessment procedures

Numerous fatigue assessment methods have been introduced to assess the durability of metal structures under cyclic loading. Finite element (FE) modelling is an integral part of most design and analysis work and methods have evolved as the analysis possibilities have become more sophisticated and computers have increased in speed and memory capacity. Fatigue assessment places two conflicting demands on the analysts. The fatigue damage process itself is highly local, thus requiring a fine FE mesh. On the other hand, welded structures are frequently large and geometrically complex, they have numerous load input locations and they have boundary conditions which may be difficult to define. These demands are best satisfied with a large FE model. Because of this conflict, fatigue assessment is frequently the slowest link in the design process of welded structures.

The fatigue resistance and fatigue life of welded joints can be evaluated based on fatigue testing or analysis using the nominal stress method, the hot spot method, the notch stress/strain method or crack growth simulations based on linear elastic fracture mechanics. The different assessment methods are described in detail in the IIW recommendations on fatigue[1] and will not be repeated here.




a) Longitudinal shear loaded fillet weld

b) Longitudinal normal loaded fillet weld

c) Transverse normal non-load carrying fillet weld

d) Transverse normal load-carrying fillet weld, toe cracking

e) Transverse load-carrying fillet weld, root cracking

NOTE Dotted lines indicate fatigue critical points.

**Figure 2 — Joint classification determination based on joint loading/function**



## 5.4 Classification of weld imperfections and features

The designation and the classification of weld imperfections and features depends on both the material being joined (e.g. steel or aluminium) and the joining process (e.g. fusion welding, pressure welding, etc.).

A general designation system for imperfections of welding and allied process is contained in ISO/TS 17845[9], which covers both metallic and non-metallic materials. A classification of geometric imperfections in metallic materials is given for fusion welding in ISO 6520-1[10] and for welds made with in ISO 6520-2[11]. Neither standard includes classifications for metallurgical imperfections.

The geometric weld imperfections for fusion welding in ISO 6520-1 are relevant for arc and beam welding processes covering metallic materials: steel, nickel, titanium, aluminium and their alloys. The document contains the relevant classification of geometric imperfections for these welding processes but no information about the relevant quality level or limits are provided.

Acceptance limits for the imperfections defined in ISO 6520-1 are given in order to define quality levels. For arc-welded joints (excluding beam welding) in steel, nickel, titanium and their alloys, quality levels are defined in ISO 5817[12] and for aluminium and its alloys, the quality levels are defined in ISO 10042[13]. For electron and laser beam welded joints in steel, quality levels are defined in ISO 13919-1[14] and for aluminium and its alloys, in ISO 13919-2[15]. For laser-arc hybrid welding of steels, nickel and nickel alloys there are quality levels for imperfections in ISO 12932[17].

In these International Standards, which define quality levels and limits, the following quality classes are used:

— quality class B refers to high quality requirements;

— quality class C refers to middle quality requirements;

— quality class D refers to low quality requirements.

However, these acceptance limits have weak relation to fatigue as stated above. For more details on this, see Reference [28].

# 6 Weld quality levels for fatigue loaded structures

## 6.1 Assessment of weld quality

The imperfections and their classification into quality groups are mostly done by the guidance of introduced codes. One standard for weld quality is ISO 5817, an adoption of DIN 8563, which was established as a standard for communication between the welders and the inspectors. The classification criterion was the difficulty, the expenses or the efforts to fabricate or to inspect by NDT. So by nature, ISO 5817 has limits in direct application to fatigue problems; it is inconsistent in respect to fatigue properties and needs application guidance. In the 2014 version, an additional Annex C is present, where some requirements are given in relation to fatigue. Most dedicated design codes specify a general quality level according to ISO 5817 and give additional regulations. In this situation, the IIW fatigue design recommendations have extended the scope of usual fatigue design codes by describing the fatigue properties of joints containing weld imperfections on a scientific basis.

After inspection and detection of a weld imperfection, the first step of the assessment procedure is to determine the type and the effect of the imperfection by categorization as given in Table 1. If a weld imperfection cannot be clearly associated to a type or an effect of imperfections as listed here, it is recommended that it is assumed to be crack-like. The interpretation of additive imperfections is that they are adding their impact on fatigue, e.g. an undercut and a small toe radius. Competitive imperfections are not influencing each other and so will compete in being the most critical one, e.g. an inner pore and a small toe radius.



**Table 1 — Categorization and assessment procedure for weld imperfections**

| Effect of imperfection | | Type of imperfection | Assessment |
|---|---|---|---|
| **Rise of general stress level** | | Misalignment | Formulae for effective stress concentration |
| **Local notch effect** | **Additive** | Weld shape imperfections, undercut | Tables given |
| | **Competitive** | Porosity and inclusions not near the surface | Tables given |
| **Crack-like imperfection** | | Cracks, lack of fusion and penetration, all types of imperfections other than given here | Fracture mechanics |

## 6.2 Requirements for a production standard weld quality

### 6.2.1 General

In as-welded joints, the fatigue resistance is given by a so called FAT class (MPa). This is the stress range at 2 × $10^6$ cycles for a certain survival probability, see FAT in nomenclature above. The spacing of the grid of resistance S-N-curves corresponds to a factor of $\sqrt[20]{10}$ = 1,122 and so they are arranged in certain defined steps. The other fatigue resistance values in this document also give the data in the same way for 2 × $10^6$ cycles.

### 6.2.2 Effect of toe geometry

#### 6.2.2.1 General

Several assessment procedures do not consider the important effects of toe geometry. These are the nominal stress and the structural hot spot procedures, which reflect the toe geometries of the specimens which have been tested for the establishing of the codes or recommendations. The consequence is a wide scatter in the experimental results. There are two assessment procedures, by which the effects can be covered: the effective notch stress method and the fracture mechanics evaluation.

The governing parameters for fatigue properties failing from the weld toe are the toe radius, $r$, the weld transition angle, $\alpha$, the weld throat and the wall thicknesses of the joined plates (see Figure 1).

Various attempts have been made to derive the fatigue properties directly from the shape of the weld toe transition. For those calculations, three geometrical parameters have been used, such as weld toe radius, weld toe angle and wall thickness.

The mostly used formulae for the stress raising notch effect of the toe have been developed by References [18], [19] and [20]. When calculating a notch factor, $K_t$, it has to be considered that the transition from $K_t$ to $K_f$ is dependent of the stress gradient in thickness direction, and so also from the wall thickness, where $K_t$ is the geometric stress concentration factor and $K_f$ is the stress concentration factor which is effective for fatigue.

Since the weld toe radii ($r$) mainly depend on the welding procedure in shop and are independent from the wall thickness, the ratio of radius to wall thickness ($r/t$) varies, which in consequence leads to a dependence of fatigue properties of wall thickness, the so called thickness effect. Nominal and structural hot spot stress methods do not consider the geometric parameters of the weld toe. They need an extra compensation for the effect of wall thickness. Notch stress and fracture mechanics include this effect.

The fatigue resistance values for the effective notch stress method (with model radius of, for example, 1 mm) have been directly derived from re-calculation of experimental data and so the effect of the transition from $K_t$ to $K_f$ is implicitly considered. Using fracture mechanics crack propagation calculations, the decline of stress in thickness direction reduces the crack growth rate accordingly and thus considers the effect of the stress gradient.

#### 6.2.2.2 Toe radius in butt welds

The effect of the toe radius is directly covered by the effective notch and fracture mechanics method. This effect is not covered in the nominal and structural hot spot stress method and thus their effects might be estimated by the use of Table 2 and Table 3.

The assessment of the toe radius may be done after Reference [29]. The used exponent for the effect of radius, $r$, was taken as 0,125 and that on wall thickness, $t$, as 0,2.

Table 2 shows the relative factor on fatigue resistance at different wall thicknesses and transition radii, where the basic FAT value of 90 corresponds to 100 % or a factor 1,00 for a thickness of 25 mm, taken from the thickness effect. Table 2 is applicable for the nominal stress approach and translated data to FAT is given in Table 3; note that $r/t$ > 0,02 (see Reference [29]). The tables also have assumed a “thinness” effect although this needs to be verified by tests.

$$\Delta\sigma \propto \left(\frac{r}{t}\right)^{0,125} \text{ and } \Delta\sigma \propto \left(\frac{25}{t}\right)^{0,2}$$

For more details about the thickness effect, see Reference [36].

**Table 2 — Maximal usable factor on fatigue resistance at different wall thickness, *t*, and transition radius, *r*, for butt welds**

| Transition radius | Wall thickness | | | |
|---|---|---|---|---|
| *r* mm | *t* mm | | | |
| | 6 | 12 | 25 | 50 |
| 0,2 | 1,19 | 1,03 | 1,00 | 0,87 |
| 0,3 | 1,25 | 1,09 | 1,00 | 0,87 |
| 0,5 | 1,33 | 1,16 | 1,00 | 0,87 |
| 1 | 1,45 | 1,26 | 1,09 | 0,95 |
| 2 | 1,58 | 1,38 | 1,19 | 1,04 |
| 3 | 1,66 | 1,45 | 1,25 | 1,09 |

**Table 3 — Maximal usable FAT levels on fatigue resistance at different wall thickness, *t*, and transition radius, *r*, for butt welds**

| Transition radius | Wall thickness | | | |
|---|---|---|---|---|
| *r* mm | *t* mm | | | |
| | 6 | 12 | 25 | 50 |
| 0,2 | 100 | 90 | 90 | 71 |
| 0,3 | 112 | 90 | 90 | 71 |
| 0,5 | 112 | 100 | 90 | 71 |
| 1 | 125 | 112 | 90 | 80 |
| 2 | 140 | 112 | 100 | 90 |
| 3 | 140 | 125 | 112 | 90 |
| NOTE FAT values always take the next lower level when the calculated value is in between the steps. | | | | |



#### 6.2.2.3 Toe radius in fillet welds

The effect of the toe radius is directly covered by the effective notch and fracture mechanics method. This effect is not covered in the nominal and structural hot spot stress method, and thus should be assessed by the use of Table 4. The IIW fatigue resistance is FAT 63, 71 or 80 depending on the type of fillet joint. Table 4 shows the relative factor on fatigue resistance at different wall thicknesses and transition radii, where the basic FAT value corresponds to 100 % or a factor 1,00 for a thickness of 25 mm, taken from the thickness effect. The table is applicable for the nominal stress approach and translated data to a basic FAT 80 is given in Table 5, note that $r/t$ > 0,02 see Reference [29]. The tables also have assumed a “thinness” effect although this needs to be verified by tests.

The assessment of the toe radius may be done after Reference [29]. The used exponent for the effect of radius, *r*, was taken as 0,125 mm and that on wall thickness, *t*, as 0,3 (see Table 4 and Table 5):

$$\Delta\sigma \propto \left(\frac{r}{t}\right)^{0,125} \text{ and } \Delta\sigma \propto \left(\frac{25}{t}\right)^{0,3}$$

**Table 4 — Maximal usable factor on fatigue resistance at different wall thickness, *t*, and transition radius, *r*, for fillet welds**

| Transition radius | Wall thickness | | | |
|---|---|---|---|---|
| *r*<br>mm | *t*<br>mm | | | |
| | 6 | 12 | 25 | 50 |
| 0,2 | 1,37 | 1,11 | 1,00 | 0,81 |
| 0,3 | 1,44 | 1,17 | 1,00 | 0,81 |
| 0,5 | 1,53 | 1,25 | 1,00 | 0,81 |
| 1 | 1,67 | 1,36 | 1,09 | 0,89 |
| 2 | 1,82 | 1,48 | 1,19 | 0,97 |
| 3 | 1,92 | 1,56 | 1,25 | 1,02 |
| NOTE FAT values always take the next lower level when the calculated value is in between the steps. | | | | |

**Table 5 — Maximal usable FAT levels (using a basic FAT 80 fillet joint) on fatigue resistance at different wall thickness, *t*, and transition radius, *r*, for fillet welds**

| Transition radius | Wall thickness | | | |
|---|---|---|---|---|
| *r*<br>mm | *t*<br>mm | | | |
| | 6 | 12 | 25 | 50 |
| 0,2 | 100 | 80 | 80 | 63 |
| 0,3 | 112 | 90 | 80 | 63 |
| 0,5 | 112 | 100 | 80 | 63 |
| 1 | 125 | 100 | 80 | 71 |
| 2 | 140 | 112 | 90 | 71 |
| 3 | 140 | 125 | 100 | 80 |
| NOTE FAT values always take the next lower level when the calculated value is in between the steps. | | | | |



The factors given in the Table 4 and Table 5 are theoretical values. The usable fatigue strength may be limited by the effect of various weld imperfections. This is applicable especially for thin wall thicknesses and in relation to the weld width (see also References [1] and [36]).

### 6.2.3 Effect of misalignment

#### 6.2.3.1 General

Misalignment in axially loaded joints leads to an increase of stress in the welded joint due to the occurrence of secondary shell bending stresses. The resulting stress is calculated by stress analysis or by using the formulae for the stress magnification factor $k_m$. It can easily be seen that misalignment is a very important factor in fatigue.

Some allowance for misalignment is already included in the tables of classified structural details (Table 6). In particular, the data for transverse butt welds already include a misalignment of up to 10 % of wall thickness dependent of the execution of the weld, which results in an increase of stress up to 30 %. For cruciform joints, a misalignment of up to 15 % of wall thickness is included, which leads to an increase of stress up to 45 %. Only exceeding misalignments need to be considered. The effective stress magnification factor $k_{m,eff}$ becomes:

$$k_{m,eff} = \frac{k_{m,calculated}}{k_{m,alreadycovered}}$$

For joints containing both linear and angular misalignment, both stress magnification factors should be applied using the formula:

$$k_m = 1 + \left(k_{m,axial} - 1\right) + \left(k_{m,angular} - 1\right)$$

For angular misalignment, there is also a straightening effect. See more in Reference [28].

**Table 6 — Consideration of stress magnification factors due to misalignment[1]**

| Type of $k_m$ analysis | Nominal stress approach | Structural hot spot, effective notch approach and linear fracture mechanics | |
|---|---|---|---|
| **Type of welded joint** | **$k_m$ already covered in FAT class** | **$k_m$ already covered in S-N curves** | **Default value of effective $k_m$ to be considered in stress** |
| Butt joint made in shop in flat position | 1,15 | 1,05 | 1,10[a] |
| Other butt joints | 1,30 | 1,05 | 1,25[a] |
| cruciform joints | 1,45 | 1,05 | 1,40[a] |
| Fillet welds on one plate surface | 1,25 | 1,05 | 1,20[b] |

[a] But not more than $(1 + 2{,}5 \times e_{max}/t)$, where $e_{max}$ is the permissible misalignment and $t$ is the wall thickness of loaded plate.

[b] But not more than $(1 + 0{,}2 \times t_{ref}/t)$, where $t_{ref}$ is the reference wall thickness of fatigue resistance curves.

### 6.2.3.2 Misalignment in butt welds

The effects of misalignment may be assessed by the use of Table 6. A certain amount of misalignment is already covered in the catalogue of structural details; for butt joints, it is $k_m = 1{,}3$ which is equivalent to a misalignment $e < 10$ % of the thickness, $t$. A possible higher misalignment at smaller wall thicknesses should be checked. For more results, see References [1], [28] and [36].

In Table 7, the effect of axial misalignment, $e$, is given by a factor to the basic fatigue resistance FAT (MPa) on an as-welded butt weld allowing up to 10 % misalignment, thus already included in the table. Note that the table is applicable for the nominal stress method only.

**Table 7 — Maximal usable factor on fatigue resistance at different wall thicknesses and misalignments for butt welds**

| Usable factor | Wall thickness | | | |
|---|---|---|---|---|
| *e*<br>mm | *t*<br>mm | | | |
| | 6 | 12 | 25 | 50 |
| 0,5 | 1,04 | 1,16 | 1,23 | 1,26 |
| 1 | 0,87 | 1,04 | 1,16 | 1,23 |
| 2 | 0,65 | 0,87 | 1,05 | 1,16 |
| 5 | — | 0,58 | 0,81 | 1,00 |
| 10 | — | — | 0,59 | 0,81 |

### 6.2.3.3 Misalignment in fillet welds

The effects of misalignment in a transverse loaded cruciform joint may be assessed by the use of the Table 6. A certain amount of misalignment is already covered in the catalogue of structural details; for load carrying fillet joints, it is $k_m$ = 1,45 which is equivalent to a misalignment $e$ < 15 % of the thickness, $t$. A possible higher misalignment at smaller wall thicknesses should be checked.

In Table 8, the effect of axial misalignment, *e*, is given by a factor to the basic fatigue resistance FAT on an as-welded cruciform joint, where the catalogue of structural details allows a misalignment of up to 15 % of primary plate thickness, thus already included in the table. Note that the table is applicable for the nominal stress method only. Note also that in non-load carrying joints, a linear misalignment has a minor influence, however, angular misalignment do. See more data in References [1], [28] and [36].

**Table 8 — Maximal usable factor on fatigue resistance at different wall thicknesses and misalignments for fillet welds**

| Usable factor | Wall thickness | | | |
|---|---|---|---|---|
| *e*<br>mm | *t*<br>mm | | | |
| | 6 | 12 | 25 | 50 |
| 0,5 | 1,16 | 1,29 | 1,37 | 1,41 |
| 1 | 0,97 | 1,16 | 1,29 | 1,37 |
| 2 | 0,73 | 0,97 | 1,17 | 1,29 |
| 5 | — | 0,64 | 0,91 | 1,12 |
| 10 | — | — | 0,66 | 0,91 |

## 6.2.4 Effect of undercut

### 6.2.4.1 General

The basis for the assessment of undercut is the ratio $u/t$, i.e. depth of undercut to plate thickness. Though undercut is an additive notch, it is already considered to a limited extent in the tables of fatigue resistance of classified structural details. Undercut does not reduce fatigue resistance of welds which are only loaded parallel to the weld seam. Experimental results and data from literature lead eventually to the acceptance levels in Table 9. See Reference [1].



**Table 9 — Acceptance levels for weld toe undercut in steel**

| Fatigue class | Allowable undercut *u*/*t* | |
|---|---|---|
| | Butt welds | Fillet welds |
| 100 | 0,025 | Not applicable |
| 90 | 0,05 | Not applicable |
| 80 | 0,075 | 0,05 |
| 71 | 0,10 | 0,075 |
| 63 | 0,10 | 0,10 |
| 56 and lower | 0,10 | 0,10 |
| NOTE 1 Undercut deeper than 1 mm assessed like a crack. | | |
| NOTE 2 This table is valid for plate thicknesses from 10 mm to 20 mm. | | |

### 6.2.4.2 Undercut in butt welds

The effect of undercut can be assessed directly by the use of the effective notch stress or fracture mechanics method. A rapid assessment may be done using Table 9.

### 6.2.4.3 Undercut in fillet welds

The effect of undercut can be assessed directly by the use of the effective notch stress or fracture mechanics method. A rapid assessment may be done using Table 9.

## 6.2.5 Effect of cold laps

### 6.2.5.1 General

When the welding process is not correct, a so-called "cold lap" might be the result. It occurs when the melted weld material do not fully merge with the plate material, leaving a non-fused zone at the weld toe. In the worst case, the cold lap is all along the weld, but sometimes the cold lap is very local, for instance, when caused by spatter. This is a defect oriented in parallel to the plate surface, often very small (microscopic), but sometimes bigger for instance when overflow of weld material occurs.

Studies made on this crack-like defect reveals that the growth direction, at least for a weld under tension, will quickly change from being in parallel to the plate at the start to a direction being perpendicular to the plate.

Table 10 gives FAT values for cold laps; see Reference [28] where analysis of a non-load carrying fillet weld and a two-sided welded butt joint have been carried out. Note that a well-done blasting operation after welding probably will prevent the small cold laps (<0,1 mm to 0,3 mm) to grow to failure.



**Table 10 — Acceptance limits for weld toe cold laps in steel**

| Fatigue class | Allowable cold lap sizes mm | |
|---|---|---|
| | Butt welds | Fillet welds |
| 63 | 1,0 | 1,0 |
| 71 | 1,0 | 0,1 |
| 80 | 1,0 | 0,1 |
| 90 | 1,0 | Not applicable |
| 100 | 0,1 | Not applicable |

#### 6.2.5.2 Cold laps in butt welds

The cold lap is conservatively assumed to be continuous along the fusion line and is described as being in parallel with the ground plate line. The allowable FAT-levels are described above, see Table 10. It is assumed that a blasting operation after welding will prevent a lot of cold laps to develop into failures.

#### 6.2.5.3 Cold laps in fillet welds

The cold lap is conservatively assumed to be continuous along the fusion line and is described as being in parallel with the ground plate line. The allowable FAT-levels are described above, see Table 10. It is assumed that a blasting operation after welding will prevent a lot of cold laps to develop into failures.

### 6.2.6 Effect of inclusions and porosity

#### 6.2.6.1 General

Embedded volumetric discontinuities, such as porosity and inclusions, are considered as competitive weld imperfections which can provide alternative sites for fatigue crack initiation than those covered by the fatigue resistance tables of classified details. The difference between the allowable size at as-welded and thermally stress relieved components is attributed to the effusion of hydrogen in annealed welds.[24][25] New Japanese investigations suggest that at least at thick-walled structures, higher allowable sizes at as-welded joints could be possible.

Before assessing the imperfections with respect to fatigue, it should be verified that the conditions apply for competitive notches, i.e. that the anticipated sites of crack initiation in the fatigue resistance tables do not coincide with the porosity and inclusions to be assessed and no interaction is expected. It is important to ensure that there is no interaction between multiple weld imperfections, be it from the same or different type. Evaluations of fatigue test results containing different types of inclusions and porosity result in Table 11.

**Table 11 — Acceptance levels for porosity and inclusions in welds in steel**

| Fatigue class | Maximum length of an inclusion mm | | Limits of porosity[a, b] |
|---|---|---|---|
| | As-welded | Stress relieved[c] | |
| 112 | — | — | 3 |
| 100 | 1,5 | 7,5 | 3 |
| 90 | 2,5 | 19 | 3 |
| 80 | 4 | 58 | 3 |
| 71 | 10 | No limit | 5 |
| 63 | 35 | No limit | 5 |
| 56 and lower | No limit | No limit | 5 |

[a] Area of radiograph.

[b] Max pore diameter or width of inclusion < 1/4 thickness or 6 mm.

[c] Stress relieved by post weld heat treatment.

Surface breaking pores and blowholes are usually detected by visual inspection and repaired. Thus, no specific recommendations are given here.

#### 6.2.6.2 Inclusions and porosity in butt welds

The effect of inclusions and porosity may be assessed using Table 11.



### 6.2.6.3 Inclusions and porosity in fillet welds

The effect of inclusions and porosity may be assessed using Table 11.

### 6.2.7 Effect of cracks and crack-like imperfections

Planar discontinuities, cracks or crack-like defects are identified by non-destructive testing and inspection. NDT indications are idealized as elliptical cracks for which the stress intensity factor is calculated. A simplified procedure has been developed which is based on the integration of the crack propagation law from an initial defect size $a_i$ to defect size of 75 % of wall thickness. This cracked component has a lower Wohler S-N-curve than initial one as stated by the FAT-levels. The new fatigue class can be calculated and tabulated in advance. In the tables, e.g. in Tables 12, 13 and 14, the stress ranges at 2 × $10^6$ cycles corresponding to the definition of the fatigue classes (FAT) of classified structural details are shown.

The real problem in non-destructive testing is the determination of the dimensions of a crack or a crack-like imperfection. These dimensions are used as the initial flaw size and are needed for calculative assessment. It is hoped that in the near future, imaging procedures will be available, by which these dimensions are directly visible. This point is important because all fracture mechanics procedures are sensitive to the location and dimensions of the initial flaw.

A rapid and conservative assessment may be done by the use of Table 12. Different crack geometries have been used to calculate the fatigue life of the joint. The tables give the fatigue resistance at 2 × $10^6$ cycles in MPa for different initial crack dimensions, $a_i$, and different wall thicknesses, $t$. The dimensions of the crack are derived from the circumscribing ellipse, see Figure 3 and Figure 4.

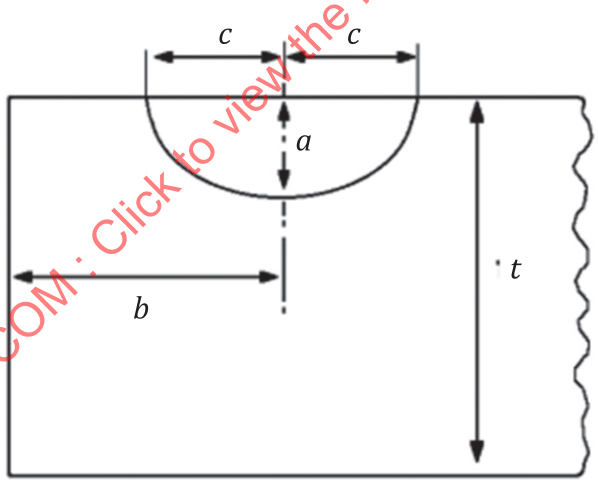



**Figure 3 — Dimensions of a surface crack, *b* = distance to nearest edge**

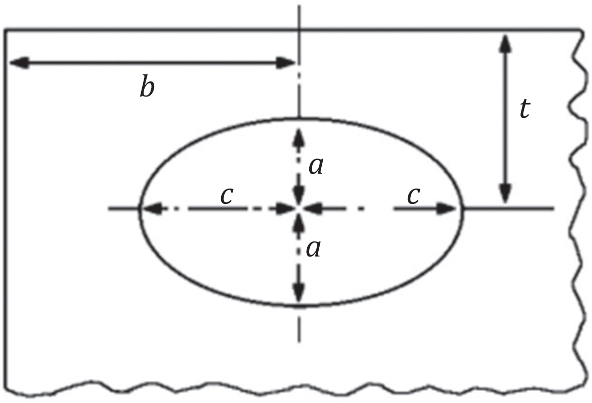



**Figure 4 — Dimensions of a crack, *tb* = distance to nearest surface**

**Table 12 — Computed stress ranges at 2 × 10⁶ cycles, characteristic values for surface cracks at butt weld toes**

Dimensions in MPa

| $a_i$ | Long surface crack near plate edge, butt welds, $a/c$ = 0,1 | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 7 | 17 |
| 20,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 6 | 8 | 11 | 20 |
| 16,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 7 | 9 | 11 | 15 | 23 |
| 12,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 9 | 12 | 14 | 16 | 20 | 27 |
| 10,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 9 | 12 | 15 | 18 | 20 | 23 | 29 |
| 8,0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 7 | 9 | 13 | 17 | 19 | 22 | 23 | 26 | 32 |
| 6,0 | 0 | 0 | 0 | 0 | 0 | 6 | 9 | 12 | 15 | 18 | 22 | 25 | 26 | 28 | 30 | 35 |
| 5,0 | 0 | 0 | 0 | 0 | 6 | 10 | 13 | 16 | 18 | 22 | 25 | 28 | 29 | 31 | 33 | 38 |
| 4,0 | 0 | 0 | 0 | 5 | 10 | 14 | 18 | 21 | 23 | 26 | 29 | 31 | 33 | 34 | 36 | 40 |
| 3,0 | 0 | 0 | 7 | 11 | 16 | 21 | 24 | 27 | 29 | 31 | 34 | 36 | 37 | 38 | 40 | 43 |
| 2,0 | 5 | 11 | 16 | 20 | 26 | 30 | 32 | 34 | 36 | 38 | 40 | 42 | 43 | 44 | 45 | 48 |
| 1,0 | 2 | 29 | 33 | 36 | 40 | 43 | 45 | 46 | 47 | 49 | 51 | 52 | 52 | 53 | 53 | 54 |
| 0,5 | 41 | 45 | 48 | 50 | 53 | 55 | 57 | 58 | 58 | 59 | 60 | 60 | 60 | 60 | 60 | 59 |
| 0,2 | 61 | 64 | 66 | 68 | 69 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 69 | 69 | 68 | 64 |
| *T* | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 | 25 | 30 | 35 | 40 | 50 | 100 |
| $a_i$ | Long surface crack apart from edge, butt welds, $a/c$ = 0,1 | | | | | | | | | | | | | | | |
| 25,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 13 | 23 |
| 20,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 11 | 13 | 17 | 26 |
| 16,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9 | 12 | 15 | 18 | 21 | 29 |
| 12,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 15 | 18 | 21 | 23 | 26 | 33 |
| 10,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 15 | 19 | 22 | 25 | 27 | 29 | 36 |
| 8,0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 12 | 15 | 20 | 24 | 27 | 29 | 31 | 33 | 39 |
| 6,0 | 0 | 0 | 0 | 0 | 0 | 12 | 16 | 19 | 22 | 26 | 30 | 32 | 34 | 35 | 37 | 43 |
| 5,0 | 0 | 0 | 0 | 0 | 11 | 17 | 20 | 24 | 26 | 30 | 33 | 35 | 37 | 38 | 40 | 45 |
| 4,0 | 0 | 0 | 0 | 9 | 17 | 22 | 26 | 29 | 31 | 34 | 37 | 39 | 41 | 42 | 44 | 48 |
| 3,0 | 0 | 0 | 13 | 18 | 25 | 29 | 32 | 35 | 37 | 40 | 42 | 44 | 45 | 46 | 48 | 51 |
| 2,0 | 11 | 19 | 25 | 29 | 35 | 38 | 41 | 43 | 45 | 47 | 49 | 50 | 51 | 52 | 53 | 55 |
| 1,0 | 33 | 39 | 43 | 46 | 50 | 53 | 54 | 56 | 57 | 59 | 60 | 61 | 61 | 61 | 62 | 61 |

**Table 12** *(continued)*

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0,5 | 52 | 56 | 59 | 61 | 64 | 66 | 67 | 68 | 68 | 69 | 69 | 69 | 69 | 69 | 68 | 66 |
| 0,2 | 74 | 77 | 78 | 79 | 80 | 81 | 81 | 80 | 80 | 80 | 79 | 78 | 77 | 76 | 75 | 70 |
| *T* | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 | 25 | 30 | 35 | 40 | 50 | 100 |
| $a_i$ | **Short surface crack apart from edge, butt welds, $a/c$ = 0,5** | | | | | | | | | | | | | | | |
| 25,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 23 | 36 |
| 20,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 21 | 24 | 29 | 40 |
| 16,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 18 | 23 | 27 | 30 | 34 | 43 |
| 12,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21 | 27 | 32 | 35 | 37 | 41 | 47 |
| 10,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 27 | 33 | 37 | 39 | 41 | 44 | 50 |
| 8,0 | 0 | 0 | 0 | 0 | 0 | 0 | 18 | 24 | 28 | 34 | 39 | 42 | 44 | 46 | 48 | 52 |
| 6,0 | 0 | 0 | 0 | 0 | 0 | 23 | 30 | 34 | 37 | 42 | 46 | 48 | 50 | 51 | 53 | 56 |
| 5,0 | 0 | 0 | 0 | 0 | 22 | 31 | 36 | 39 | 42 | 47 | 50 | 52 | 53 | 54 | 56 | 57 |
| 4,0 | 0 | 0 | 0 | 20 | 32 | 38 | 43 | 46 | 48 | 52 | 54 | 56 | 57 | 58 | 59 | 60 |
| 3,0 | 0 | 0 | 26 | 33 | 42 | 47 | 51 | 53 | 55 | 58 | 59 | 61 | 61 | 62 | 62 | 62 |
| 2,0 | 22 | 36 | 43 | 48 | 54 | 58 | 60 | 62 | 63 | 65 | 66 | 67 | 67 | 67 | 67 | 65 |
| 1,0 | 54 | 61 | 65 | 68 | 71 | 73 | 74 | 74 | 75 | 75 | 75 | 75 | 74 | 74 | 73 | 69 |
| 0,5 | 76 | 80 | 82 | 83 | 84 | 84 | 84 | 84 | 84 | 83 | 82 | 81 | 80 | 79 | 77 | 71 |
| 0,2 | 98 | 98 | 98 | 98 | 97 | 95 | 94 | 93 | 92 | 90 | 88 | 86 | 85 | 83 | 81 | 74 |
| *T* | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 | 25 | 30 | 35 | 40 | 50 | 100 |

**Table 13 — Computed stress ranges at 2 × 10$^6$ cycles, characteristic values for embedded cracks**

Dimensions in MPa

| $a_i$ | **Embedded long crack near plate edge, $a/c$ = 0,1** | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 7 | 17 |
| 20,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 5 | 7 | 11 | 20 |
| 16,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 6 | 9 | 11 | 14 | 24 |
| 12,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 8 | 11 | 14 | 16 | 19 | 28 |
| 10,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 8 | 12 | 15 | 17 | 19 | 23 | 31 |
| 8,0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 6 | 8 | 12 | 16 | 19 | 22 | 24 | 27 | 35 |
| 6,0 | 0 | 0 | 0 | 0 | 0 | 5 | 9 | 12 | 14 | 18 | 22 | 25 | 27 | 29 | 32 | 40 |
| 5,0 | 0 | 0 | 0 | 0 | 5 | 9 | 12 | 15 | 18 | 22 | 26 | 28 | 31 | 32 | 35 | 43 |
| 4,0 | 0 | 0 | 0 | 4 | 9 | 14 | 17 | 20 | 23 | 26 | 30 | 33 | 35 | 37 | 39 | 47 |
| 3,0 | 0 | 0 | 6 | 10 | 16 | 20 | 24 | 27 | 29 | 32 | 36 | 38 | 40 | 42 | 45 | 52 |
| 2,0 | 4 | 10 | 15 | 19 | 25 | 30 | 33 | 36 | 38 | 41 | 44 | 46 | 48 | 50 | 52 | 59 |
| 1,0 | 22 | 29 | 33 | 37 | 42 | 46 | 49 | 51 | 53 | 56 | 59 | 61 | 63 | 64 | 67 | 73 |
| 0,5 | 42 | 47 | 52 | 55 | 60 | 63 | 66 | 68 | 69 | 72 | 75 | 77 | 79 | 80 | 82 | 88 |
| 0,2 | 68 | 73 | 77 | 80 | 84 | 87 | 90 | 92 | 93 | 96 | 98 | 100 | 101 | 103 | 105 | 110 |
| *T* | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 | 25 | 30 | 35 | 40 | 50 | 100 |
| $a_i$ | **Embedded long crack apart from plate edge, $a/c$ = 0,1** | | | | | | | | | | | | | | | |
| 25,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 19 | 30 |
| 20,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 17 | 20 | 24 | 33 |
| 16,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14 | 19 | 22 | 25 | 29 | 37 |
| 12,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 22 | 26 | 29 | 31 | 34 | 41 |
| 10,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | 22 | 27 | 30 | 33 | 35 | 37 | 44 |
| 8,0 | 0 | 0 | 0 | 0 | 0 | 0 | 14 | 19 | 23 | 28 | 32 | 35 | 37 | 39 | 41 | 48 |

**Table 13** *(continued)*

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6,0 | 0 | 0 | 0 | 0 | 0 | 19 | 24 | 28 | 31 | 35 | 38 | 41 | 42 | 44 | 46 | 53 |
| 5,0 | 0 | 0 | 0 | 0 | 18 | 25 | 29 | 33 | 35 | 39 | 42 | 44 | 46 | 47 | 49 | 56 |
| 4,0 | 0 | 0 | 0 | 15 | 26 | 31 | 35 | 38 | 40 | 43 | 46 | 48 | 50 | 51 | 54 | 59 |
| 3,0 | 0 | 0 | 21 | 27 | 35 | 39 | 42 | 45 | 46 | 49 | 52 | 54 | 56 | 57 | 59 | 64 |
| 2,0 | 17 | 29 | 35 | 40 | 45 | 49 | 51 | 53 | 55 | 58 | 60 | 62 | 64 | 65 | 67 | 71 |
| 1,0 | 44 | 51 | 55 | 58 | 62 | 65 | 67 | 69 | 70 | 73 | 75 | 77 | 78 | 79 | 80 | 84 |
| 0,5 | 65 | 69 | 73 | 75 | 79 | 82 | 84 | 85 | 86 | 88 | 90 | 91 | 92 | 93 | 94 | 97 |
| 0,2 | 91 | 95 | 98 | 100 | 103 | 105 | 106 | 107 | 108 | 110 | 111 | 112 | 112 | 113 | 114 | 117 |
| *T* | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 | 25 | 30 | 35 | 40 | 50 | 100 |
| $a_i$ | **Embedded short crack apart from plate edge, *a*/*c* = 0,5** | | | | | | | | | | | | | | | |
| 25,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 27 | 41 |
| 20,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 24 | 28 | 34 | 46 |
| 16,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 27 | 32 | 35 | 40 | 50 |
| 12,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24 | 32 | 37 | 41 | 43 | 47 | 55 |
| 10,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 23 | 32 | 38 | 42 | 45 | 48 | 51 | 58 |
| 8,0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 28 | 33 | 40 | 45 | 48 | 51 | 53 | 56 | 62 |
| 6,0 | 0 | 0 | 0 | 0 | 0 | 27 | 35 | 40 | 43 | 48 | 53 | 56 | 58 | 59 | 62 | 67 |
| 5,0 | 0 | 0 | 0 | 0 | 26 | 36 | 42 | 46 | 49 | 54 | 57 | 60 | 62 | 63 | 66 | 71 |
| 4,0 | 0 | 0 | 0 | 23 | 37 | 44 | 49 | 53 | 56 | 60 | 63 | 65 | 67 | 68 | 70 | 75 |
| 3,0 | 0 | 0 | 31 | 39 | 49 | 54 | 58 | 61 | 64 | 67 | 70 | 71 | 73 | 74 | 76 | 80 |
| 2,0 | 26 | 42 | 50 | 55 | 62 | 67 | 70 | 72 | 74 | 76 | 79 | 80 | 81 | 82 | 84 | 87 |
| 1,0 | 62 | 70 | 75 | 78 | 83 | 86 | 88 | 89 | 91 | 92 | 94 | 95 | 96 | 97 | 98 | 100 |
| 0,5 | 88 | 93 | 96 | 99 | 102 | 104 | 105 | 106 | 107 | 108 | 110 | 110 | 111 | 112 | 112 | 115 |
| 0,2 | 118 | 121 | 123 | 124 | 126 | 128 | 129 | 129 | 130 | 131 | 132 | 133 | 133 | 134 | 135 | 137 |
| *t* | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 | 25 | 30 | 35 | 40 | 50 | 100 |

**Table 14 — Computed stress ranges at 2 × 10⁶ cycles, characteristic values for Surface cracks at fillet weld toes**

Dimensions in MPa

| $a_i$ | **Long surface crack near plate edge, fillet welds, *a*/*c* = 0,1** | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 7 | 16 |
| 20,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 6 | 8 | 11 | 19 |
| 16,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 7 | 9 | 11 | 15 | 22 |
| 12,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 9 | 12 | 14 | 16 | 19 | 25 |
| 10,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 9 | 12 | 15 | 17 | 19 | 22 | 27 |
| 8,0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 7 | 9 | 13 | 16 | 19 | 21 | 22 | 25 | 30 |
| 6,0 | 0 | 0 | 0 | 0 | 0 | 6 | 9 | 12 | 15 | 18 | 21 | 23 | 25 | 26 | 28 | 33 |
| 5,0 | 0 | 0 | 0 | 0 | 6 | 10 | 13 | 16 | 18 | 21 | 24 | 26 | 28 | 29 | 31 | 35 |
| 4,0 | 0 | 0 | 0 | 5 | 10 | 14 | 18 | 20 | 22 | 25 | 28 | 29 | 31 | 32 | 33 | 37 |
| 3,0 | 0 | 0 | 7 | 11 | 16 | 20 | 23 | 25 | 27 | 30 | 32 | 33 | 34 | 35 | 37 | 39 |
| 2,0 | 5 | 11 | 16 | 20 | 25 | 28 | 31 | 32 | 34 | 36 | 37 | 39 | 40 | 40 | 41 | 43 |
| 1,0 | 22 | 28 | 32 | 34 | 38 | 40 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 48 | 48 | 48 |
| 0,5 | 38 | 42 | 45 | 47 | 49 | 51 | 52 | 53 | 53 | 54 | 54 | 54 | 54 | 54 | 54 | 52 |
| 0,2 | 57 | 59 | 61 | 61 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 62 | 61 | 61 | 60 | 56 |
| *t* | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 | 25 | 30 | 35 | 40 | 50 | 100 |



**Table 14** *(continued)*

| $a_i$ | Long surface crack apart from edge, fillet welds, $a/c$ = 0,1 | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 13 | 22 |
| 20,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 11 | 13 | 17 | 25 |
| 16,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9 | 12 | 15 | 18 | 21 | 28 |
| 12,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 15 | 18 | 21 | 23 | 26 | 32 |
| 10,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 15 | 19 | 22 | 24 | 26 | 28 | 34 |
| 8,0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 12 | 15 | 20 | 24 | 26 | 28 | 29 | 32 | 37 |
| 6,0 | 0 | 0 | 0 | 0 | 0 | 12 | 16 | 19 | 22 | 26 | 29 | 31 | 33 | 34 | 36 | 40 |
| 5,0 | 0 | 0 | 0 | 0 | 11 | 17 | 20 | 24 | 26 | 29 | 32 | 34 | 35 | 36 | 38 | 42 |
| 4,0 | 0 | 0 | 0 | 9 | 17 | 22 | 26 | 28 | 30 | 33 | 36 | 37 | 39 | 40 | 41 | 44 |
| 3,0 | 0 | 0 | 13 | 18 | 25 | 29 | 32 | 34 | 36 | 38 | 40 | 42 | 43 | 44 | 45 | 47 |
| 2,0 | 11 | 19 | 25 | 29 | 34 | 37 | 39 | 41 | 42 | 44 | 46 | 47 | 48 | 49 | 50 | 51 |
| 1,0 | 32 | 38 | 42 | 44 | 48 | 50 | 52 | 53 | 54 | 55 | 56 | 57 | 57 | 57 | 57 | 56 |
| 0,5 | 50 | 53 | 56 | 58 | 60 | 62 | 63 | 63 | 64 | 64 | 64 | 64 | 63 | 63 | 62 | 59 |
| 0,2 | 70 | 72 | 73 | 74 | 75 | 75 | 74 | 74 | 74 | 73 | 72 | 71 | 70 | 69 | 67 | 62 |
| *t* | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 | 25 | 30 | 35 | 40 | 50 | 100 |
| $a_i$ | Short surface crack apart from edge, fillet welds, $a/c$ = 0,5 | | | | | | | | | | | | | | | |
| 25,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 23 | 35 |
| 20,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 21 | 24 | 29 | 38 |
| 16,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 18 | 23 | 27 | 30 | 34 | 42 |
| 12,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21 | 27 | 32 | 35 | 37 | 40 | 45 |
| 10,0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 27 | 33 | 36 | 39 | 41 | 43 | 47 |
| 8,0 | 0 | 0 | 0 | 0 | 0 | 0 | 18 | 24 | 28 | 34 | 39 | 41 | 43 | 45 | 47 | 49 |
| 6,0 | 0 | 0 | 0 | 0 | 0 | 23 | 30 | 34 | 37 | 42 | 45 | 47 | 48 | 49 | 51 | 52 |
| 5,0 | 0 | 0 | 0 | 0 | 22 | 31 | 36 | 39 | 42 | 46 | 48 | 50 | 51 | 52 | 53 | 53 |
| 4,0 | 0 | 0 | 0 | 20 | 32 | 38 | 42 | 45 | 47 | 50 | 52 | 54 | 54 | 55 | 55 | 55 |
| 3,0 | 0 | 0 | 26 | 33 | 42 | 47 | 50 | 52 | 53 | 55 | 57 | 58 | 58 | 58 | 58 | 57 |
| 2,0 | 22 | 36 | 43 | 48 | 53 | 56 | 58 | 60 | 61 | 62 | 62 | 62 | 62 | 62 | 62 | 59 |
| 1,0 | 53 | 60 | 63 | 66 | 68 | 69 | 70 | 70 | 70 | 70 | 69 | 69 | 68 | 67 | 66 | 62 |
| 0,5 | 74 | 76 | 78 | 78 | 79 | 78 | 78 | 77 | 77 | 76 | 74 | 73 | 72 | 71 | 69 | 64 |
| 0,2 | 92 | 91 | 91 | 90 | 88 | 86 | 85 | 84 | 83 | 81 | 79 | 77 | 75 | 74 | 72 | 65 |
| *t* | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 | 25 | 30 | 35 | 40 | 50 | 100 |



## 6.3 Design of Experiments (DoE) using simulation

### 6.3.1 General

Using the effective notch method, many of the above listed imperfection-effects can be modelled and one way to show the impact on fatigue is to use Design of Experiments (DoE)[34]. In such an approach, the physical experiments normally used are replaced by simulations. The parameters are, in this case, assigned two levels: one high and one low, preferably on each side of normal values.

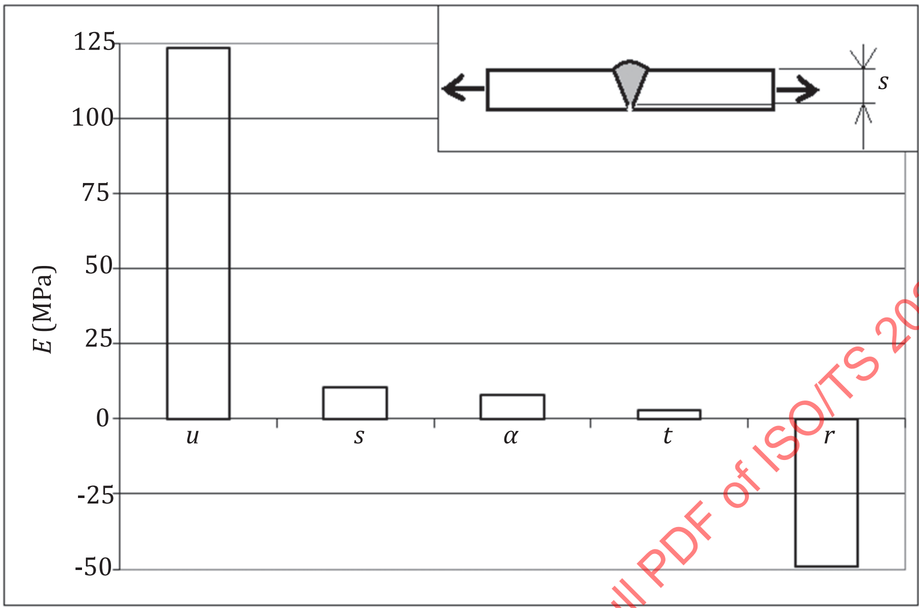
EXAMPLE 1 If normally, a thickness of 10 mm is used, then high level could be 12 mm and low level 8 mm.

EXAMPLE 2 If normally, a throat size of 5 mm is used, then high level could be 6 mm and low level 4 mm.

Levels are chosen by the user, reflecting the range where the results are applicable. A more detailed explanation of the DoE-method is given in 7.4.

### 6.3.2 Parameters using the effective notch method on butt welds

Studying a one-sided and a (symmetric) two-sided butt weld where thickness, penetration, angle, undercut and weld toe radius are given two levels (high and low) and computing the effect of these on the weld toe stresses, the result shown in Figures 5 and 6 can be found.




**Key**

*u* undercut, from 0,1 mm to 1 mm

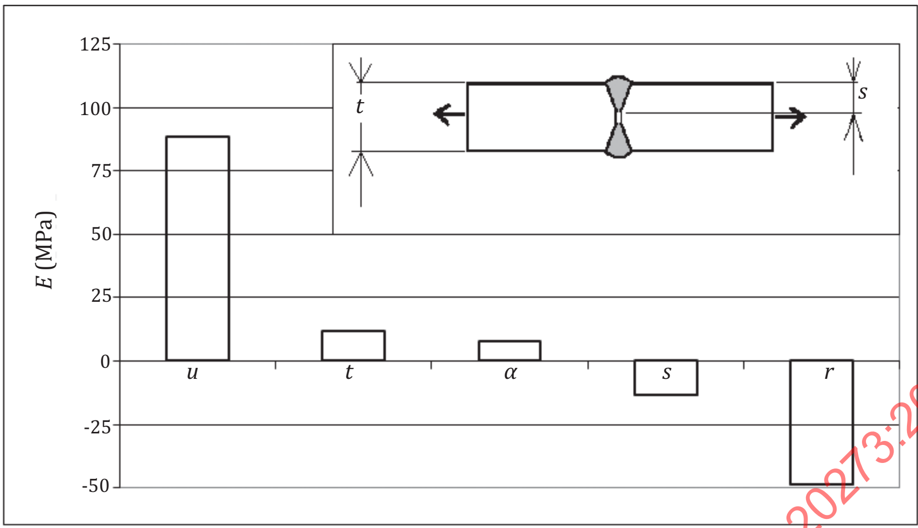
*s* s-measure, from $t$−0,1 mm to $t$−1 mm

*α* weld angle, from 10° to 30°

*t* thickness, from 8 mm to 12 mm

*r* weld toe radius, from 1 mm to 2 mm

**Figure 5 — Results presented as *E*-effects on principal stresses in the weld toe for a one-sided butt joint, with an applied nominal stress range of 100 MPa**




**Key**

*u* undercut, from 0,1 mm to 1 mm
*s* -measure, from *t*/2−0,1 mm to *t*/2−1 mm
*α* weld angle, from 10° to 30°
*t* thickness, from 10 mm to 20 mm
*r* weld toe radius, from 1 mm to 2 mm

**Figure 6 — Results presented as *E*-effects on principal stresses in the weld toe for a two-sided butt joint, with an applied nominal stress range of 100 MPa**

As seen, the most important parameters concerning the weld outside are the undercut and the weld toe radius. Other parameters, penetration, thickness and angle, play a smaller roll under the circumstances modelled. Note that Figure 5 and Figure 6 reflect the stress at the weld toe and not the weld root side, but the critical point for these cases is normally the weld root side whenever there is not a full penetration. See more in Clause 7.

### 6.3.3 Parameters using the effective notch method on fillet welds

Studying a load-carrying (LC) and non-load carrying (non-LC) fillet in a cruciform joint weld where thickness, penetration, angle, undercut and weld toe radius are given two levels (high and low) and compute the effect of these on the weld toe stresses, the result shown in Figure 7 and Figure 8 can be found.

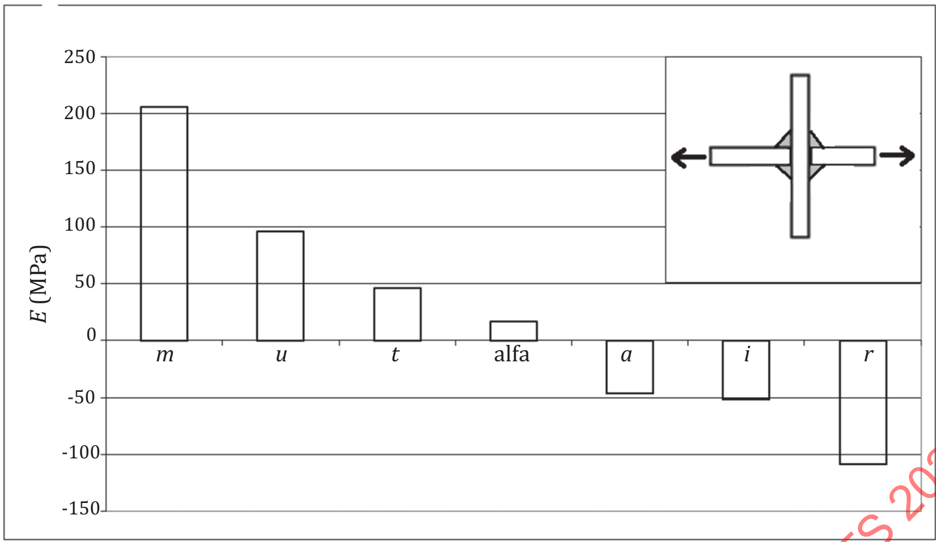



**Figure 7 — Results presented as E-effects on principal stresses in the weld toe for a load-carrying (LC) fillet joint, with an applied nominal stress range of 100 MPa**

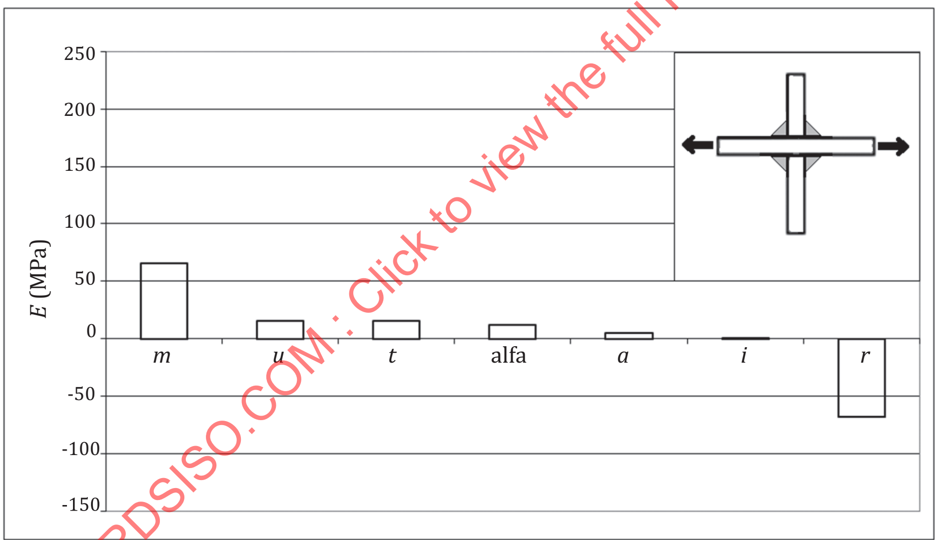



**Figure 8 — Results presented as E-effects on principal stresses in the weld toe for a non-load-carrying (non-LC) fillet joint, with an applied nominal stress range of 100 MPa**

For both cases (Figure 7 and Figure 8), the parameters vary as follows:

— *m* = misalignment, from 0,1 mm to 1,5 mm;

— *u* = undercut, from 0,1 mm to 1 mm;

— *t* = thickness, from 8 mm to 12 mm;

— *α* = weld angle, from 30° to 60°;

— *a* = throat-size, from 4 mm to 6 mm;

— *i* = penetration, from 1 mm to 3 mm;

— *r* = weld toe radius, from 1 mm to 2 mm.

The first observation is that the influence from the parameters concerning the weld outside is much higher on a LC-joint (Figure 7) compared to a non-LC-joint (Figure 8). Consequently, weld quality plays a more important role in load-carrying joints compared to non-load-carrying joints. Next is that the most important parameters are the undercut, the weld toe radius and misalignment (LC only), much the same as for a butt welds. Other parameters, penetration, thickness, angle and throat play a medium or smaller roll under the circumstances modelled.

NOTE The critical point for the LC-case is normally the weld root side whenever there is not a full penetration (the figures reflect the stress at the weld toe and not the weld root side).

## 6.4 Fatigue design of high quality welds

### 6.4.1 General

The term “high quality” is used for welds with a lower level of imperfections than usually accepted. Further on, it is used for welds which are produced under a higher level of control during assembly, accuracy of fit, welding and inspection of the welded component. Thus, the scatter of fatigue strength can be reduced and higher stresses might be allowable. In addition, the fatigue strength may be verified by fatigue testing of the component.

The level of control and inspection is laid down in several standards as, for example, in ISO 3834 (all parts)[26] where three levels are specified. A further approach is given in EN 1090[5][6][7]. Here, execution classes EXC1 to EXC4 are specified and related to the quality groups D to B+ of ISO 5817 with additional requirements in EN 1090. The questions of consistence in terms of fatigue in ISO 5817 are not addressed and are still open. One industrial standard used within Volvo CE has been developed, where acceptance limits are formulated to relate to fatigue (see Reference [51]) here one quality level is aiming to reflect the fatigue described within IIW Recommendations and there are further two higher and one lower quality level. Apart from stating a connection to fatigue Reference [51] has at least two main differences compared to ISO 5817: firstly, the focus is put on the weld toe transition area and thus requirements on the toe radii are important. Secondly, a requirement is defined of the penetration of the weld, stated as a measure on the drawing (see further in 7.2). These points support the designer to establish an appropriate weld quality level on the drawing in order to reflect fatigue. Also, it makes it possible to develop adapted weld processes in workshop to match the different weld designations on the drawing[35].

All benefits of the high quality welds vanish if significant imperfections are present (weakest link theory). Then, Tables 12, 13 and 14 apply.

### 6.4.2 Effect of improvement methods

The fatigue strength can be improved by different methods of post-weld treatments. The benign effect of some improvement methods is already known and it is already applied at large series productions. In this case, the fatigue strength has to be verified by test. The new update of the IIW recommendations has a real novelty, which is a calculative verification of fatigue properties at post weld treatments. Only factors are given, without a consideration to a possibly flatter slope of the Wohler S-N-curves (with the exception of HFMI treated welds).

The practically applied methods can be divided into two groups: improvement of shape and improvement of residual stress conditions. The IIW recommendations specify the improvement of the weld toe by burr grinding, by TIG dressing and by hammer and needle peening. It has to be born in mind that only such welds can be improved, at which the possible crack at the weld toe is governing, see Figure 9.

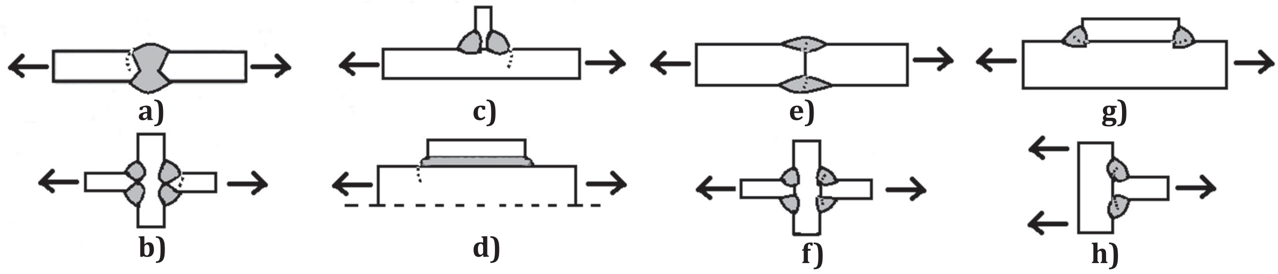



**Figure 9 — Cases suitable for improvement (a to d) and cases not suitable (e to h)**



It has to be always verified if another spot of a possible crack initiation could become dominant and governing for the fatigue assessment. This is especially the case at un-welded root gaps or faces, at embedded imperfections and in cases where the direction of loading is parallel to the notch, e.g. in longitudinally loaded welds seams.

Recently made research has also looked at the so called high frequency mechanical improvement (HFMI) post treatment[33]. Here, the toe area is treated imposing residual stresses, which improves fatigue properties and even a beneficial effect from the material yield limit can be utilized.

### 6.4.3 Improvement of shape of weld toe

The shape improvement methods considered in the IIW recommendations are grinding of the toe and TIG dressing of the toe. The smoothening of the weld toe transition results in a reduction of the notch effect and thus improves the fatigue properties. The improvement is given by a factor in terms of stress. For quality control in shop, a data sheet has been developed equivalent to weld procedure specification (WPS) sheet.

Guidance for improvement of welds and the benefit from improvement in terms of fatigue are given in ISO 3834 (all parts)[26]. If even higher benefits from improvement are claimed, that has to be verified by tests. An adequate production quality insurance system should be established in order to ensure that the product quality is at least that of the test.

### 6.4.4 Improvement by compressive residual stress

Hammer peening, needle peening and high frequency mechanical improvement (HFMI)[33] introduce a residual compressive stress which is beneficial for the fatigue properties. Some requirements in loading have to be met at the application of the method. There is a limitation in compressive load stresses in order to avoid an overstressing in compression, which after unloading could relax the residual compressive stress, which was introduced by the improvement procedure.

# 7 Root side requirements

## 7.1 General

When designing a weld, it is often desirable that the root side has a greater or at least the same fatigue life as the toe side. The reason is that weld toe cracking is visually easier to detect compared to root cracking. Also, a repair is generally more difficult to perform on a root crack compared to a toe crack. For more information on weld root design, see Reference [37].

## 7.2 Joints with weld root as weakest point

Following the principles of “design for purpose”, the analysis should focus on the identification of the weak points of the weld (toe or root) when loading is applied to the component, see also 5.1. In such an approach, there is a big difference between load carrying and non-load carrying welds. A butt weld should always be regarded being load carrying since the loads and stresses pass through the weld. For fillet welds, the variations are bigger and some may be regarded as non-load carrying while others are to be regarded as fully load carrying, which thus have the highest requirements. Whichever case, one could state that for load carrying cases, the root side commonly becomes critical, while for non-load carrying cases, the toe side often is critical. It is thus important to focus on parameters governing the stress levels in these points.

## 7.3 Designation for penetration

When a weld is designed and given the designations on the drawing, it is common to state the quality level according to some standard; here, ISO 5817 is often used. Further, for a fillet joint, the throat size needs to be determined and given. In most cases, this is all that is stated on the drawing and if so, this implies a weld root side designation which may become unclear.

In order to reach a more detailed designation, it is important that the weld back side is addressed and this can be made through specification of the penetration, see Figure 10 and Figure 11.


**Figure 10 — Partial penetration in a butt joint, *s*-measure is used**

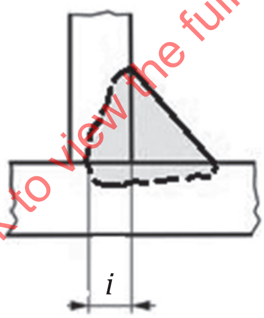



**Figure 11 — Partial penetration in a fillet joint, *i*-measure is used**

If the partial penetration is considered in design process of welded joints, then the value of the penetration should be described as a requirement on the drawing, either as *s*-measure for a butt weld or as *i*-measure for a fillet weld (note that "*i*" is the gap penetration, not the side penetration). It can be given along with all other designations; for example, along with the throat-size designation: "*i*2*a*5" (meaning that $i$ = 2 mm and $a$ = 5 mm), so that it is clear in the work shop which of the demands to focus on during welding.

In this way, it becomes possible for the designers to differentiate the requirements on the different parts of the weld: if the weld root side is critical, then attention can be given to the needed penetration and if the weld outside (toe) is critical, then attention can be given to the quality level. Following the principle of "design and weld for purpose", this can lead to a weld designation on the drawing, which is varied along the weld. This may be used to reach a longer fatigue life in high stressed parts and lower welding cost in low stressed areas.

To understand the influence of different parameters on the weld fatigue life, it is of interest to get an overview of how they act. Below, this is shown in an example of variations in parameters and their influence on the weld root side. The analysis is made using the effective notch method[3] and the results are presented according to the theory for Design of Experiments (DoE)[34].

## 7.4 Design of Experiments in load carrying joints

Consider a load carrying cruciform joint and two welded butt joints, both having load carrying characteristics. These joints will, in most cases of partial penetration, show a critical point at the root side if tension is applied. The weld toe might also be critical depending on the weld parameters and quality levels but this is not taken into account here.

The situation can be studied by applying the methods in Design of Experiments (DoE) and make use of simulations. DoE methods are, typically and in general, used for physical test setups where many parameters have an effect on the result and where a full test setup varying all parameters is too expensive or time consuming. In such a case, using DoE theories, it is possible to reduce the number of tests and still get valuable information of the important parameters.

But the DoE-method can also be utilized by replacing the physical tests with simulations. In such a case, a full test setup can be used since all that is needed is a parametric model and computation time. The simplest way is to vary the interesting parameters at two levels, one high and one low, preferably with values on each side of the typical or nominal one. Results are then applicable within the interval used.

By combining N parameters and vary them one at a time (resulting in 2N computer simulations due to two levels), the results can be studied statistically finding out what their individual influences are. One can also see any combined effect between them, if there is one. Adding all results (notch stresses at the weld root in this case) including signs (minus for "low" and plus for "high parameter level) and then averaging, gives the so-called "*E*-effect" which reflects the influence from a certain parameter. If a positive summary is reached, then an increase in this parameter increases the stress in the joint and if a negative summary is reached, then an increase in this parameter decreases the stress in the joint. Consequently, if the sum for a certain parameter is near zero or "small", then this parameter has a low importance. The parameters (or combinations of parameters) with a "small" effect in the stress level may be regarded as scatter (and could be compared to the scatter occurring in physical tests). This is done by calculating the standard deviation (Stdv) of all effects, so for example, a parameter may be regarded as significant if an effect is greater than, say, one (1) Stdv.

The above described DoE method, has been carried out for two butt welds (a one-sided and a two-sided) and one load carrying cruciform joint, all in tension, and the result is shown in Figure 12, Figure 13 and Figure 14, respectively.

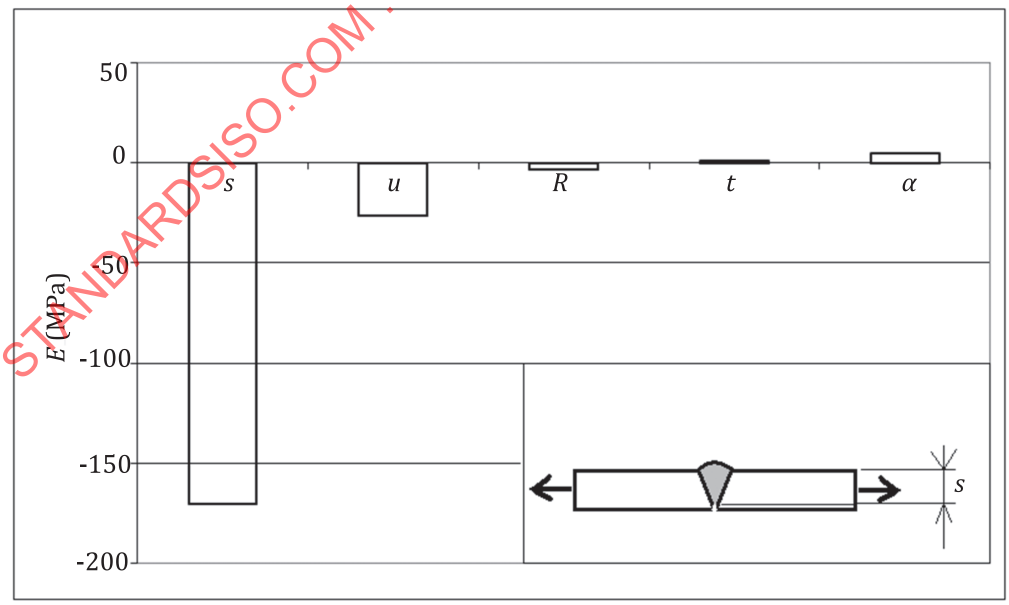



**Figure 12 — Computed effects in weld root of a one-sided welded butt joint**

Results are presented as *E*-effects on principal stresses in the weld toe for a one-sided butt joint, with an applied nominal stress range of 100 MPa. The parameters vary as follows:

— *s* = s-measure, from *t*–0,1 mm to *t*–1 mm;

— *u* = undercut, from 0,1 mm to 1 mm;

— *r* = weld toe radius, from 1 mm to 2 mm;

— *t* = thickness, from 8 mm to 12 mm;

— *α* = weld angle, from 10° to 30°.

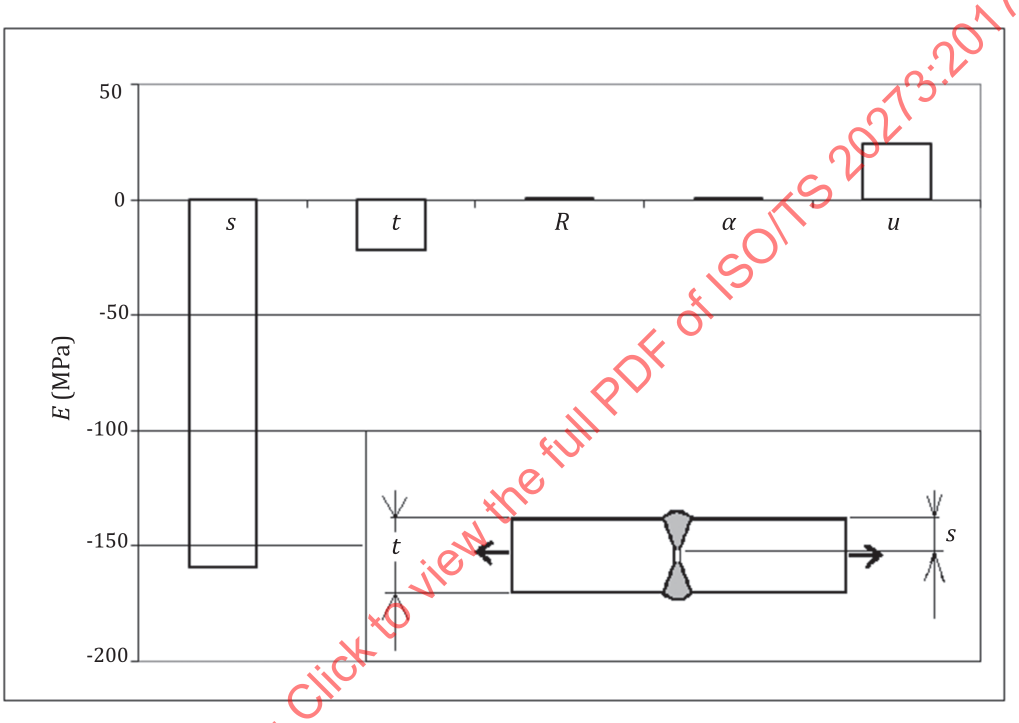





**Figure 13 — Computed effects in weld root of a two-sided welded butt joint**

Results are presented as *E*-effects on principal stresses in the weld toe for a two-sided butt joint, with an applied nominal stress range of 100 MPa. The parameters vary as follows:

— *s* = s-measure, from *t*/2–0,1 mm to *t*/2–1 mm;

— *t* = thickness, from 10 mm to 20 mm;

— *r* = weld toe radius, from 1 mm to 2 mm;

— *α* = weld angle, from 10° and 30°;

— *u* = undercut, from 0,1 mm to 1 mm.

The result indicates that for both types of these butt joints, the only main effect on the weld root stress is the lack of penetration (*t*–2*s*-measure if full penetration is not present). The thickness has some effect, even though not so high: the stress level will decrease when the thickness is increased.

Note that in the “IIW Recommendations” of fatigue design, the butt joints normally are given FAT-values around 71 MPa to 90 MPa. However, if NDT is not made on the root side, the FAT-value is lowered to 36 MPa and the reason for this is the impact from not fully penetrated welds, when the critical point is changed from weld toe to weld root.

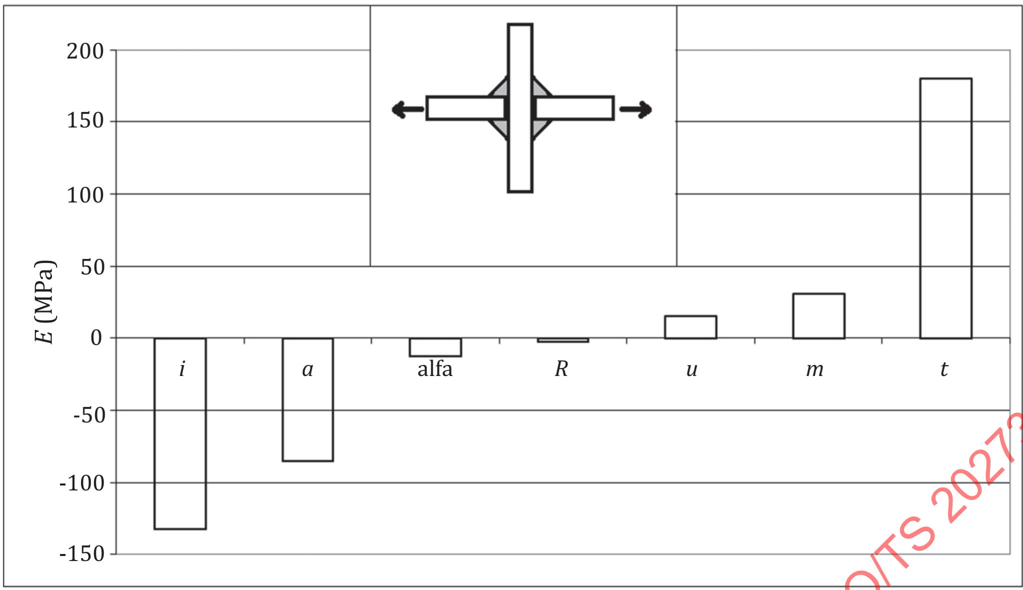



**Figure 14 — Computed effects in weld root of a load carrying cruciform joint**



Results are presented as *E*-effects on principal stresses in the weld root for a load-carrying cruciform joint, with an applied nominal stress range of 100 MPa. The parameters vary as follows:

— *i* = penetration from 1 mm to 3 mm;

— *a* = throat size from 4 mm to 6 mm;

— *α* = weld angle is varied between 30° and 60°;

— *R* = weld toe radius from 1 mm to 2 mm;

— *u* = undercut from 0,1 mm to 1 mm;

— *m* = misalignment from 0,1 mm to 1,5 mm;

— *t* = thickness from 8 mm to 12 mm.

For the load-carrying fillet weld, the penetration and the throat size are significant and both should be increased since the effect is negative (implying a stress decrease effect). The thickness is also significant, but has a positive effect, which means that the stress level increases when the thickness is increased and this is probably due to the fact that the root defect size increases (root defect = $t–2i$). The effect is the opposite compared to the butt joint above. Misalignment, angle, undercut and toe radius play a very small role for obvious reasons.

Realizing that both penetration "*i*" and throat size "*a*" are significant parameters for the root side stress level of a load carrying fillet joint, it is consequently important that both these measures are stated on the drawing.

## 7.5 Throat size vs penetration

As shown above for fillet joints, the penetration is the most important parameter for weld root fatigue followed by the throat size and of course the thickness itself, see Figure 14. However, the parameters cannot be translated into each other directly; for instance, an increase of 1 mm penetration in a fillet weld is often worth much more than 1 mm more throat size[38] where 1 mm more penetration approximately equals 2 mm less nominal throat size regarding fatigue life. Many times, the max (or sometimes called total) throat size a tot, which includes both nominal throat and the penetration, *i*, is used as a combined effect. However, this is not a good representation of the fatigue strength even though this often is used in the nominal method, this is investigated below.

Studying a load carrying cruciform joint in thickness $t$ = 10 mm and comparing the nominal analysis method with the effective notch method, an interesting difference between the methods is revealed. The fillet weld can be performed with different nominal throats, $a$, and penetration depth, $i$. The question is how to describe this on the drawing (see Figure 15). Usually, a throat size, $a$, only is given and nothing is expressed about the penetration. However, there is a need to do that and this can be shown by studying three cases, which has the same max throat, $a_{tot}$. See Table 15.

**Table 15 — Three different weld throat-sizes (WTS) for $t$ = 10 mm**

| | Optimized WTS | Ordinary WTS | Excessive WTS |
|---|---|---|---|
| Nominal throat, $a_n$ (mm) | 4 | 5 | 6,4 |
| Penetration, $i$ (mm) | 3,4 | 2 | 0 |
| Max throat, $a_{tot} = a_n + i/\sqrt{2}$ (mm) | 6,4 | 6,4 | 6,4 |

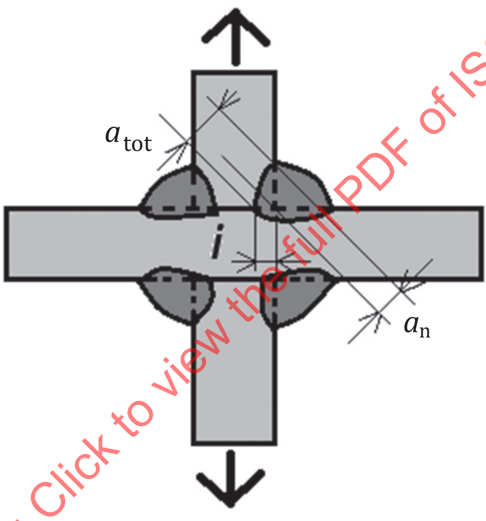
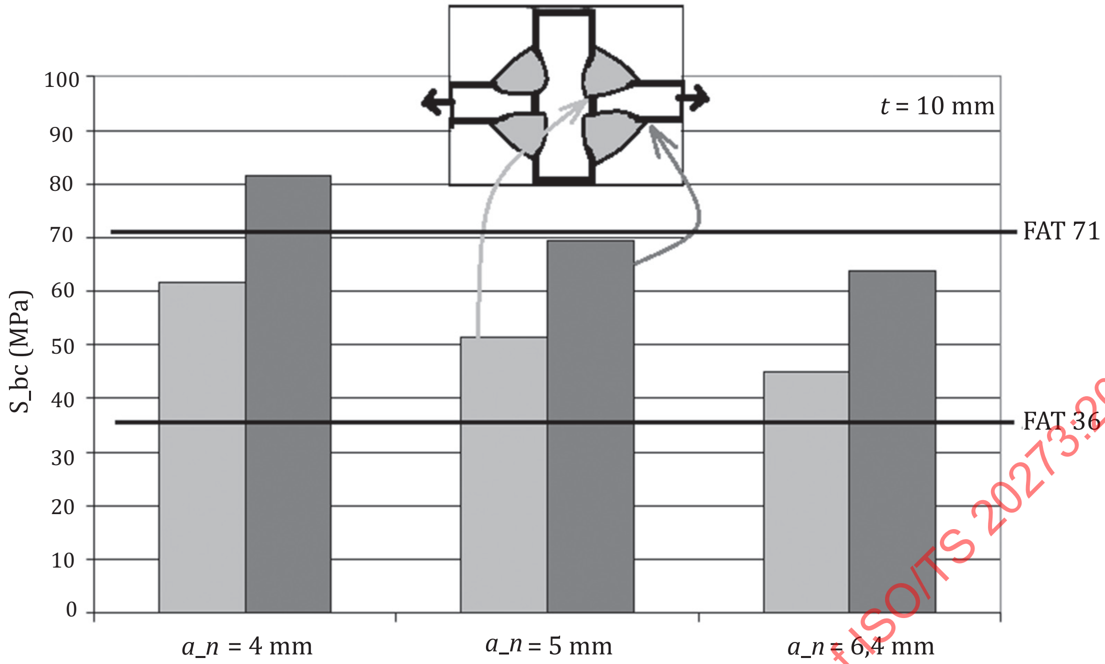



**Figure 15 — Fillet weld with partial penetration**

The analysis of these cases for the nominal method using the max throat, $a_{tot}$, gives no difference, neither for the weld toe (FAT 71 without misalignment) nor for the weld root (FAT 36)[1]. The latter point depends on the fact that the nominal method uses the max throat, which is the same in all three cases.

However, using the notch method[3], there will be a difference (for both root and toe) since a load-carrying weld with higher penetration will have a better stress path through the weld. Assuming that the notch method results are correct (stress range FAT 225 equivalent to 2 × $10^6$ cycles), the stresses can be "back" computed into the nominal world to see what would have been the applied nominal stress for the same fatigue life (2 × $10^6$ cycles), see coloured columns in Figure 16. The IIW Recommendation nominal FAT levels are also given for toe and root, respectively, as lines for comparison. Note that the notch stress method includes a "thinness"-effect, while this is not done in the nominal method for $t$ < 25 mm and this explains some of the differences.






**Key**

$a_n$ = 4 mm optimized joint

$a_n$ = 5 mm ordinary joint

$a_n$ = 6,4 mm excessive joint

**Figure 16 — "Back"-computed nominal stress ranges at 2 × 10$^6$ cycles for a cruciform joint with three different nominal throat thicknesses, $a_n$, but same max or total throat**

Looking at the results, one can firstly see that the joint in general has the lowest strength on the root side (light grey columns). The FAT 36 for the nominal method is well below the computed levels in all three cases, implying a conservative design using this method. However, using the effective notch method, one can utilize quite a big improvement taking the penetration into account: for the optimized joint ($a_n$ = 4 mm), a computed stress range of 62 MPa could be compared to FAT 36, implying a life increase of approximately five times: $(62/36)^3 \approx 5,1$.

On the weld toe side (dark grey columns), the ordinary joint ($a_n$ = 5 mm) agrees well with the nominal FAT 71; however, for the excessive one ($a_n$ = 6,4 mm), a non-conservative result is at hand using the nominal method if not FAT 63 would be assumed (note that the computation model has no misalignment while FAT 63 assumes that a misalignment is included).

Another interesting observation is that the optimized weld joint, having the smallest nominal throat size and probably the best productivity in the work shop (lowest welding time and lowest amount of consumables), also has the highest fatigue performance on both weld toe and weld root side.

The overall conclusion is thus that there is a reason to include the penetration in the weld designations on the drawing and also that this can be taken into account during the design of the joint if the effective notch method is used. A difficulty is of course the inspection of the penetration measures in production, where in, many cases, destructive methods only are available.

## 8 Fitness for service

### 8.1 General

Assessment of welds not meeting "standard" requirements may sometimes be of interest to investigate. An example is to determine the fatigue life from a found crack-like defect to failure. It is recommended to use local based methods, like the effective notch method or the fracture mechanics method with the guidance of well-established recommendations as, e.g. BS 7910[27] or comparable ones.

Fracture mechanics is used for several purposes as, for example:

a) assessment of fracture, especially brittle fracture, in a component containing cracks or crack-like details;

$$K = \sigma \cdot \sqrt{\pi \cdot a} \cdot Y_u(a)$$

b) assessment of fatigue properties in a component containing cracks or crack-like imperfection as, for example,in welded joints;

c) predicting the fatigue properties of severely notched components with no or a relatively short crack initiation phase. Welded joints behave as being severely notched. Predictions are made assuming small initial defects.

The fatigue assessment procedures as in b) and c) are performed by calculation of the growth of an initial crack, $a_i$, to a final crack size, $a_f$. The parameter which describes the fatigue action at a crack tip in terms of crack propagation is the stress intensity factor (SIF) range $\Delta K$. The starting crack configuration is the centre crack in an infinite plate. The stress intensity factor, $K$, is defined by the following formula:

$$K = \sigma \sqrt{\pi \cdot a}$$

where

$\sigma$ is the remote stress in the plate;

$a$ is the crack parameter, here half the distance from tip to tip.

In existing components, there are various crack configurations and geometrical shapes. So, corrections are needed for the deviation from the centre cracked plate. These corrections take into account the following parameters and crack locations:

a) free surface of a surface crack;

b) embedded crack located inside of a plate;

c) limited width or wall thickness;

d) shape of a crack, mostly taken as being elliptic;

e) distance to an edge.

The formula for the stress intensity factor has, due to this, to be expanded by a correction function $Y_u(a)$.

For welds with a stress distribution, the factor $Y_u(a)$ may be separated into two factors: $M_k$ for correction of the local notch and $y(a)$ for the configuration. For more details on this, see Reference [28]. In this reference, description of aspect ratios, initial flaw sizes and dimensions of cracks are also given.

## 8.2 Fatigue assessment by crack propagation

The fatigue action is then determined using the “Paris-Erdogan” power law:

$$\frac{da}{dN} = C_0 \cdot \Delta K^m \quad \text{if} \quad \Delta K < \Delta K_{\text{th}} \quad \text{then} \quad \frac{da}{dN} = 0$$

where

$a$ is the crack size;

$N$ is the number of cycles;

$\Delta K$ is the stress intensity factor range;

$\Delta K_{th}$ is the threshold value of stress intensity factor range below which no crack propagation is assumed;

$C_0$ is the material constants.

Safety considerations, influence of stress ratio, etc. may be taken into account (see more in Reference [28]).

## 8.3 Material parameters for crack propagation

The material data used in Paris law can be found in Tables 16 and 17. In the absence of specified or measured material parameters, the values given below are recommended. They are characteristic values (see Clause 4 and Reference [1]).

**Table 16 — Parameters of the Paris power law and threshold data for steel**

| Units | Paris power law parameters | Threshold values $\Delta K_{th}$ | | | |
|---|---|---|---|---|---|
| | | $R \geq 0,5$ | $0 \leq R \leq 0,5$ | $R < 0$ | Surface crack depth <1 mm |
| $K$ (Nmm$^{-3/2}$)<br>$da/dN$ (mm/cycle) | $C_0 = 5,21 \times 10^{13}$<br>m = 3,0 | 63 | $170 - 214 \times R$ | 170 | ≤63 |
| $K$ (MPa√m)<br>$da/dN$ (m/cycle) | $C_0 = 1,65 \times 10^{11}$<br>m = 3,0 | 2,0 | $5,4 - 6,8 \times R$ | 5,4 | ≤2,0 |

**Table 17 — Parameters of the Paris power law and threshold data for aluminium**

| Units | Paris power law parameters | Threshold values $\Delta K_{th}$ | | | |
|---|---|---|---|---|---|
| | | $R \geq 0,5$ | $0 \leq R \leq 0,5$ | $R < 0$ | Surface crack depth <1 mm |
| $K$ (Nmm$^{-3/2}$)<br>$da/dN$ (mm/cycle) | $C_0 = 1,41 \times 10^{11}$<br>m = 3,0 | 21 | $56,7 - 72,3 \times R$ | 56,7 | ≤21 |
| $K$ (MPa√m)<br>$da/dN$ (m/cycle) | $C_0 = 4,46 \times 10^{10}$<br>m = 3,0 | 0,7 | $1,8 - 2,3 \times R$ | 1,8 | ≤0,7 |

For elevated temperatures other than room temperature or for metallic materials other than steel, the crack propagation parameters vary with the modulus of elasticity, $E$, and may be determined accordingly.

$$C = C_{0,\text{steel}} \left( \frac{E_{\text{steel}}}{E} \right)^m \qquad \Delta K_{\text{th}} = \Delta K_{\text{th,steel}} \left( \frac{E}{E_{\text{steel}}} \right)$$

## 8.4 Formulae for stress intensity factors

### 8.4.1 General

Stress intensity factor formulae may be taken from literature.[32],[40],[41],[42],[43],[44],[45],[46] The formulae given below address only some of the cases relevant to welded joints. They are given as a base for two examples, which follow below.

### 8.4.2 Standard solutions

#### 8.4.2.1 Stress intensity factors for surface cracks under membrane stress

The formula for the stress intensity factor $K_1$is valid for $a/c < 1$, see also Reference [1].

$$K_1 = \sigma \sqrt{\frac{\pi a}{Q}} \cdot F_s$$

where

$Q$ = $1 + 1{,}464\,(a/c)^{1{,}65}$;

$F_s$ = $[M_1 + M_2 \times (a/t)^2 + M_3 \times (a/t)^4] \times g \times f \times f_w$;

$M_1$ = $1{,}13 - 0{,}09\,(a/c)$;

$M_2$ = $-0{,}54 + 0{,}89 / (0{,}2 + a/c)$;

$M_3$ = $0{,}5 - 1 / (0{,}65 + a/c) + 14\,(1 - a/c)^{24}$;

$f_w$ = $\{\sec[\pi \times c\,\sqrt{(a/t)}/(2 \times b)]\}^{½}$.

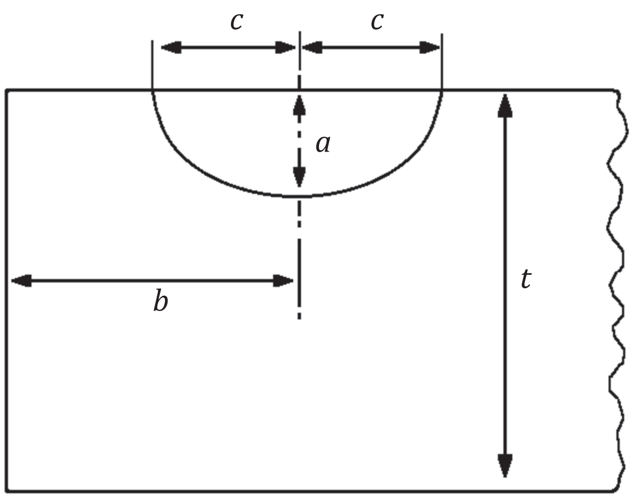
g and f are dependent on direction

"$a$"-direction: $g = 1$, $f = 1$

"$c$"-direction: $g = 1 + [0{,}1 + 0{,}35\,(a/t)^2]$

$f = \sqrt{(a/c)}$

See Figure 17.




**Key**

*b* distance to nearest edge

*t* thickness

*a* depth of crack

*c* width of crack

**Figure 17 — Surface crack under membrane stress**



### 8.4.2.2 Stress intensity factors for root gap crack in a fillet welded cruciform joint

The formula for the stress intensity factor, *K*, is valid for $H/t$ from 0,2 to 1,2 and for $a/w$ from 0,0 to 0,7. For more details, see Reference [32].

$$K = \frac{\sigma\left(A_1 + A_2 \cdot \dfrac{a}{w}\right)\sqrt{\pi a \cdot \sec\left(\pi \cdot a/2w\right)}}{1 + 2 \cdot H/t}$$

where

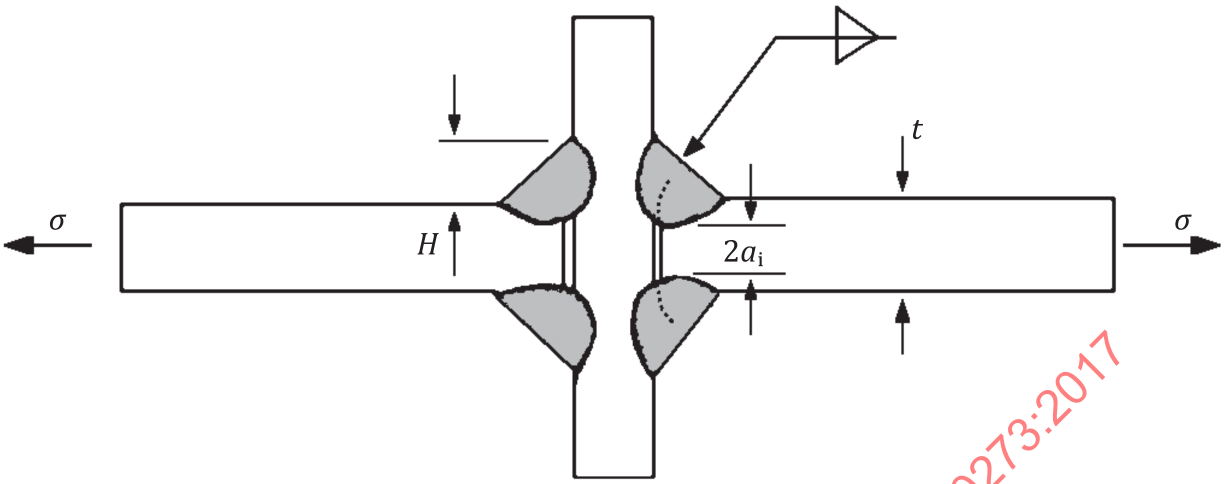
$w$ = $H + t/2$;

$\sigma$ is the nominal stress range in the longitudinal plates and with $x = H/t$;

$A_1$ = $0{,}528 + 3{,}287 \times x - 4{,}361 \times x^2 + 3{,}696 \times x^3 - 1{,}875 \times x^4 + 0{,}415 \times x^5$;

$A_2$ = $0{,}218 + 2{,}717 \times x - 10{,}171 \times x^2 + 13{,}122 \times x^3 - 7{,}755 \times x^4 + 1{,}783 \times x^5$.

See Figure 18.




**Key**

2$a_i$ initial crack size

$A$ crack size during growth

$\sigma$ tension stress

$t$ thickness

$H$ leg length

**Figure 18 — Root gap crack in a fillet welded cruciform joint**

### 8.4.3 Solutions for magnification function, $M_k$

Parametric formulae for $M_k$ functions have been established for a variety of welded joints[45][46].

Below, one formula is given, where the 3-dimensional effects are included for a semi-circular weld toe crack. The $M_k$ values are given and to get the stress intensity values, the $Y$-factors also need to be computed (see 8.4.2) where the $Y$-factor can be identified as $F_s/\sqrt{Q}$ in formulae of $K_1$.

This 3-dimensional $M_k$-solution was published by References [47] and [48] where the fitted formulae are valid for membrane stress and a weld toe angle of 45° and:

— $0{,}005 < a/t < 1{,}0$;

— $0{,}1 < a/c < 1{,}0$;

— $0{,}5 < L/t < 2{,}75$, (if $L/t > 2{,}75$ then $L/t = 2{,}75$).

See Figure 19.



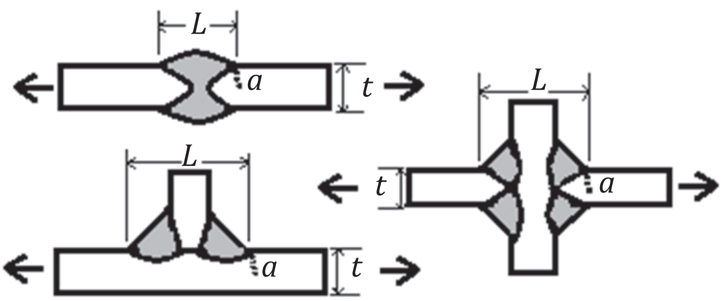



**Figure 19 — Dimensions for different joints**