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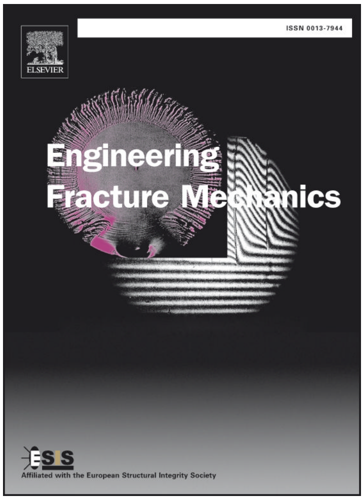

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Fracture mechanics based prediction of undercut tolerances in industry

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Abstract. Undercuts are geometrical discontinuities or grooves along the toe of a weld caused by loss of the parent material that remain unfilled by weld metal. Regardless of their causes, undercuts can be found in structures and components, in the majority of joints and most of the welding processes. Due to their frequency of appearance in welded structures and their detrimental effects on component life, undercut acceptance criteria had to be regulated by construction codes and standards. Depending on the area where the component is in service, specific tolerances must be satisfied in order to accept or reject the part. In general, undercut depth is considered to be the limiting parameter for this kind of imperfection. However, there is currently in industry no agreement about which value of depth is tolerable for a desired fatigue strength. The purposes of the present paper are twofold. First, to summarise the state of art associated to undercut tolerances in different codes, standards and recommendation documents, for different industries and applications. Secondly, to employ a fracture mechanics based methodology to predict safe undercut dimensions for butt welds subjected to fatigue. Predictions are in good agreement with experimental results from literature, and proposed method proved to be helpful for assessing weld discontinuities.

Keywords: Fatigue strength; Welded joints; Undercut; Standards; Fracture mechanics approach

List of Symbols

α	reinforcement angle of the weld
a_i	initial crack length
a_{np}	non-propagating crack length
C, m	environmental sensitive material constants
d	location of the strongest microstructural barrier (e.g. grain size)
D	undercut depth
da/dN	crack propagation rate
k	material constant that takes into account development of ΔK_C
k_t	stress concentration factor
k_m	stress magnification factor that accounts for misalignments

N	cycles in fatigue life
P	applied load in the four points bending test
ρ	undercut radius
R	stress ratio (minimum stress/maximum stress)
s, L	half the minor and major span in four points bending scheme
t	plate thickness
Y	geometrical factor
$\Delta\mathrm{K}$, $\Delta\mathrm{K}_\mathrm{I}$	applied stress intensity factor range, under Mode I
$\Delta\mathrm{K}_\mathrm{C}$	"extrinsic" component of $\Delta\mathrm{K}_\mathrm{th}$
$\Delta\mathrm{K}_\mathrm{CR}$	"extrinsic" component of $\Delta\mathrm{K}_\mathrm{thR}$
$\Delta\mathrm{K}_\mathrm{dR}$	microstructural crack propagation threshold range for $a = d$
$\Delta\mathrm{K}_\mathrm{th}$	fatigue crack propagation threshold, a function of crack length
$\Delta\mathrm{K}_\mathrm{thR}$	fatigue crack propagation threshold for long cracks (dependent on R)
$\Delta\sigma_\mathrm{N}$	nominal applied stress range
$\Delta\sigma_\mathrm{e}$	fatigue/endurance limit
$\Delta\sigma_\mathrm{eR}$	plain fatigue limit (material endurance, dependent on R)
$\sigma_\mathrm{e-1}$	stress amplitude at R = -1
σ_AeR	stress amplitude at asymmetric stress ratio, R
σ_UTS	ultimate tensile strength

1. Introduction

Historically, it was agreed that welds had to achieve a minimum level of soundness, based on good practices and good-workmanship conditions during manufacturing. Acceptability of flaws relied on experience and no scientific judgement was established. Consequently, cracks and other defects were strictly forbidden, and some tolerances were excessively stringent, leading sometimes to unnecessary and costly repair welding and productivity delays. Advances in welding technology and inspection techniques, together with researches in the field of fracture mechanics and welding metallurgy have provided deep understanding of welding processes and their relation with mechanical behaviour of welded constructions. Imperfections generated during fusion welding are nowadays well-recognised and their effects are comprehensively quantified in many studies. Particularly for undercuts, a thorough review was made in a previous publication from the authors [1]. These developments forced codes and standards to update, and criteria for deciding whether a flaw is acceptable or not also had to be reviewed. However, this was not always achieved when dealing with defects under cyclic loading.

General procedures employed in construction regulations to determine acceptance levels for weld flaws are based on quality control levels or weld quality systems, such as those in ISO 5817 [2]. Quality control levels permit flaws in the structure as long as they are less severe than limits provided. These methods are currently used in different industries for monitoring production, with satisfactory results. In cases where fatigue damage is expected, weld details are related to a specific S-N curve that defines its cyclic behaviour. However, no consistent relation exists between acceptance limits of imperfections and the actual damaging phenomenon, which constitutes the main drawback of weld quality systems.

In order to reduce costs by proper judging of unnecessary repairs, the presence of flaws with dimensions beyond quality control levels can be further analysed. In this regard, some efforts have been steered towards assessment of weld imperfections based on fitness-for-purpose/service (FFP/FFS) analyses, providing better insight of remaining fatigue life of in-service equipments. In general, FFP methods determine in a rational manner, whether a structure or component containing existing or fictitious flaws is able to perform its function, satisfactorily. Assessment against different failure modes is carried out by well-recognised engineering approaches, as well as relevant literature on similar components [3-5].

Together with current success of FFP guidelines, fracture mechanics proved to be a powerful tool to evaluate many types of discontinuities, and it´s use has spread in many application areas. Codes and standards have included guidelines on fracture mechanics, although some parameters, like threshold stress intensity factor, are usually disregarded or adopt very conservative values.

In the next two sections, literature review of relevant documents that deal with undercuts is performed. Section 4 summarises methodology employed to assess fatigue behaviour of butt welds with undercuts, corresponding results and considerations. Comparison of these outcomes with codes and standards is the scope of discussions in Section 5. Finally, conclusions are presented.

2. Literature review

Fatigue design of welded components is generally based on S-N curves, which are expressed in terms of the nominal stress. Due to some limitations in this methodology, alternative approaches have been developed to assess fatigue of defective welds, such as the structural stress approach or the hot-spot stress approach [6], the notch stress approach [7] and fracture mechanics. The last two methodologies already account for weld discontinuities. However, most design documents still employ the nominal stress approach [8, 9]. This is the simplest of all methodologies and it considers 12 S-N curves with a slope m = 3, defined from statistical analyses and empirical adjustments of extensive fatigue tests on representative weld details. Therefore, it takes into account realistic geometrical discontinuities and residual stresses. Standard basic S-N curves correspond to 97.7% survival probability, although lower values can also be adopted. Differences in fatigue life between two successive curves are approximately equivalent to one standard deviation. FAT class characterises every curve as the stress range in MPa for which cycles to failure reach $N = 2 \cdot 10^6$. High welding residual stresses and some angular distortion are included in FAT curves, but thickness effects must be considered when $t \geq 25$ mm.

Undercut tolerances are commonly related to FAT values (or equivalently, quality categories). Therefore, they have an associated S-N curve that depends on a certain geometrical parameter. Acceptance or rejection of the flaw is decided by comparing this actual quality category with the required quality category. The latter can be determined with the required stress range and design fatigue life, or alternatively with the weld quality category of the reference detail (e.g. butt joint). In the following, a summary of undercut acceptance limits in different regulations is presented.

2.1. International Institute of Welding (IIW Guidelines) [8]

The purpose of this guideline is to relate weld imperfections with fatigue strength requirements found in IIW Recommendations [9]. It is applicable to fusion welds made of steel with plate thickness over 3 mm and yield strength up to 960 MPa. Undercuts are regarded as additive imperfections, which means that they are adding their effect on fatigue behaviour (e.g., undercut and toe radius). Table 1 is given for rapid assessment of these flaws as a function of their depth to thickness ratio, *D*/*t*, based on experimental tests and results from literature [10, 11]. However, IIW recommends the effective notch stress approach or fracture mechanics for deeper analyses.

Table 1: Acceptance levels for weld toe undercuts in steel, according to IIW recommendations [8].

Fatigue class (FAT)	Allowable undercut, *D*/*t*	
	Butt welds	Fillet welds
100	0.025	Not applicable
90	0.05	Not applicable
80	0.075	0.05
71	0.1	0.075
63 and lower	0.1	0.1

2.2. SS-EN ISO 5817 [2]

This standard presents dimensions of some fusion weld imperfections normally expected in welded construction. Application is limited to fully penetrated butt joints and all fillet welds, with thickness over 0.5 mm. The latest version of ISO 5817 [2] includes fatigue considerations based on previous studies that relates weld quality systems to FAT curves for arc-welded steel components [12]. Consequently, the standard became more explicit with respect to structural performance under fatigue.

Three quality levels are provided and labelled by letters B, C and D, with the former corresponding to the highest requirement on the final weld. These groups are based on production and good workmanship. Limits proposed are directly applicable to visual testing of weldments. If loading mode is cyclic, then quality levels must additionally meet fatigue requirements in terms of FAT values. The basis of these additional requirements is that limits for imperfections in quality level C and B must be adjusted in order to satisfy fatigue class FAT 63 and FAT 90, respectively. Supplementary fatigue level FAT 125 can be assigned to weld quality B for some imperfections, although this is generally not achieved in the as-welded condition. Table 2 shows such requirements for toe undercuts. Note that level B 125 demands removal of this type of imperfection. It can also be highlighted, that a smooth transition is required, in order to achieve good-workmanship standards. This restricts the application of the document to blunt undercuts (i.e. not too sharp).

Table 2: Undercut requirements for welds subjected to fatigue loading [2].

Description	t [mm]	Limits for imperfections for quality levels		
		C 63	B 90	B 125
Continuous or intermittent undercut in butt or fillet welded joint. Smooth transition is required. It is not a symmetric imperfection.	> 3	$D \leq 0.1\ t$ but max. 0.5 mm	$D \leq 0.05\ t$ but max. 0.5 mm	Not permitted

2.3. British Standard, BS 7608 [13]

This document provides guidance and recommendations to methods for assessing high cycle fatigue of steel parts and products. Materials covered have yield strengths in the range 200 to 960 MPa and thickness over 3 mm. It can be applied to every industrial area not covered by other BS containing fatigue assessment rules, although it should not be considered a specification or code of practice. It might additionally be applied to steel building and civil engineering structures, where Eurocode 3 [14] is normally used, since the latter does not assess any weld defect or flaw individually.

Acceptance limits for undercuts were defined based on large experimental fatigue data in transversely-stressed butt and fillet steel welds, in which undercuts were either naturally generated or artificially machined at the toe. These results were analysed statistically assuming a log-normal distribution of fatigue life to obtain the lower 95% confidence limit. Quality category was determined by comparing these data with that of flawless welds. Particularly, reduction in fatigue strength due to undercut depth was quantified in terms of steps in the grid of quality category S-N curves. Parameter D/t was found to reduce scatter in experimental data [3, 10].

Requirements for undercuts are shown in Table 3. Correspondence with BS 7910 quality categories is also displayed. Due to the limited database available [10], some validity limitations apply to Table 3. First of all, it is restricted to shallow undercuts at the toe of perfectly aligned joints. Additionally, plate thickness must be in the range of 10 to 40 mm. Undercuts formed in materials out of this limits should be assessed as planar flaws following BS 7910 procedures. In cases where stresses act parallel to weld direction, there is no limiting size for undercut depth, since they do not affect fatigue behaviour under this condition.

Table 3: Fatigue based tolerances for undercuts in transversely stressed butt welds, according to BS [3, 13].

Required class (FAT)	Equivalent BS 7910 quality category	Undercut depth, *D*
		Butt welds
C	-	Not permitted
D	Q1	0.025 *t*, ≤ 1 mm
E	Q2	0.05 *t*, ≤ 1 mm
F	Q3	0.075 *t*, ≤ 1 mm
F2	Q4	0.1 *t*, ≤ 1 mm

2.4. VOLVO STD 181-0004 [15]

VOLVO made the first attempts to include fatigue consideration in old weld quality systems, which were originally based on good workmanship in fabrication [16]. Although, normal workmanship conditions are related to a certain extent to adequate weld performance, a proper analysis based on FFP was not established, especially for structures subjected to fatigue loading. As a result, this standard was developed, by considering IIW Recommendations [9]. Later, IIW published its own guideline to weld quality systems [8] and ISO added fatigue consideration to its latest edition [2].

STD 181-0004 applies to designing, production, testing and inspection of fusion-welded steel sheets, with thickness over 3 mm. Limits for different imperfections are analysed and characterised in terms of their influence to fatigue performance. This implies that tolerances for different types of imperfection should result in equal fatigue strength, for a desired weld class.

The system distinguishes between static loading (VS) and fatigue loading. The latter is further divided into four quality levels, VE, VD, VC and VB. Level VB presents the most stringent requirements and it is associated to post-treated welds. Lowest quality level, VE, demands reduced characteristics for discontinuities on the surface and it should only be used in special cases where the root quality deserves critical attention [17]. In contrast, VD and VC refer to qualities typically considered as normal and high, respectively, in as-welded components. Therefore, it is expected that VD reflects the stress level recommended by IIW [9], which can be translated into a good quality level [18], or equivalently a FAT 80. It is worthwhile mentioning that an increase in quality level to the following category is corresponded with an increase of 25% in fatigue strength. This means that VC and VB reflect FAT values of 100 and 125, respectively. Analogously, FAT 63 applies to quality level VE.

Most requirements in STD 181-0004 are based on notch-stress analyses. Jonsson et al. [18] proposed acceptance levels for undercuts based on the effective notch stress approach [7] that assigns a radius of 1 mm to the undercut root. Tolerances were obtained by considering that the worst acceptable defect is given by a stress value two standard deviations above the stress level of a normal weld, free from undercuts [18]. This limit or safe value of the stress is later compared to the stress at the root of an undercut for different depths. Current requirements for undercuts in STD 181-0004 are displayed in Table 4. Note that qualities VD and VC demand additional requirements in terms of the “outer transition radius”, which should not be lower than 0.3 mm and 1 mm, respectively. Results in Table 4 are in accordance with IIW recommendations [9], whose acceptance limits are based on Petershagen´s work [10].

Table 4: Acceptance limits for undercuts in STD 181-0004 [15].

Type of joint	Weld class				
	Static loading	Fatigue loading			
		Lowest requirements			Highest requirements
	VS	VE	VD	VC	VB
Butt joint	$D \leq 0.2\, t \leq 2$ mm.	$D \leq 0.1\, t \leq 1$ mm.	$D \leq 0.05\, t \leq 1$ mm. Toe radius $r \geq 0.3$ mm.	$D \leq 0.04\, t \leq 1$ mm. Toe radius $r \geq 1$ mm.	Not permitted unless specifically stated in written post-treatment instructions.
Fillet joint		$D \leq 0.15\, t \leq 1.5$ mm.	$D \leq 0.1\, t \leq 1.5$ mm. Toe radius $r \geq 0.3$ mm.	$D \leq 0.08\, t \leq 1$ mm. Toe radius $r \geq 1.5$ mm.	

2.5. American Welding Society, AWS D1.1-D1.1M [19]

This code covers several aspects and requirements for welding of steel buildings. It deals with carbon or low alloy steels, with thickness over 3 mm and minimum specified yield strength below 690 MPa. In its latest edition, fatigue curve cases were updated to agree with the American Institute of Steel Construction [20]. Welds are grouped into several categories, for which an S-N curve corresponds. Category C applies to cruciform joints, non-carrying load fillets and complete joint penetration butt and T- welds.

Acceptance criteria for Welding Procedure Specification (WPS) Qualification, and also for Welder and Welding Operator Qualification, limit undercut depth to 1/32” (1 mm) when performing visual inspection or macroetch tests. Additionally, all welds must meet visual acceptance criteria of Table 5 and shall be free from cracks.

Table 5: Acceptance criteria for undercuts under visual inspection, according to AWS [19].

Inspection Criteria	Statically Loaded Non-tubular Connections	Cyclically Loaded Non-tubular Connections	Tubular Connections (all loads)
For $t \leq 25$ mm, $D \leq 1$ mm, with the following exception: $D \leq 2$ mm for any accumulated length up to 50 mm in any 300 mm. For $t > 25$ mm, $D \leq 2$ mm for any length of weld.	X		
In primary members, $D \leq 0.25$ mm when the weld is transverse to tensile stress under any design loading condition. For all other cases, $D \leq 1$ mm.		X	X

2.6. American Society of Mechanical Engineers, ASME BPVC [21-23]

ASME code establishes rules for construction of boilers [21], pressure vessels [22], transport tanks, and nuclear components [23], and addresses solely safety issues related to pressure integrity.

Subsection NF in Section III [23] presents a methodology for assessing fatigue of weldments, in which the allowable stress range is determined by the loading condition and the stress category. The former depends on the number of cycles expected in the component being analysed, whereas stress categories describe the type of member and its arrangement, material and location, including welded joints. For a full penetrated butt weld with reinforcement, stress category C applies. Corresponding allowable stress range for high cycle fatigue ($N > 2\cdot10^6$) is 70 MPa, in accordance with AWS D1.1 [19]. In general, if fracture mechanics based analyses or refined fatigue assessments are necessary, API 579-1/ASME FFS-1 [4] is referred throughout the code.

With regard to weld defect tolerances, acceptance limits for undercuts are determined based on their depth. As a result of static strength considerations, undercuts whose depth is beyond a minimum section thickness are forbidden. In the case of finished longitudinal and circumferential joints in boilers [21], depth must not exceed 0.8 mm, or 10% of the wall thickness, whichever is less. Moreover, a smooth transition between the surfaces being joined is required. Defects found to be rejectable must be removed, re-welded and re-examined. Although some sections of this code do include fatigue considerations, no clear relation between undercut tolerances and cyclic loading can be established.

2.7. American Petroleum Institute, API 1104 [24]

API 1104 is intended to be used for welding pipes made of carbon and low-alloy steels, in petroleum industry. Undercuts must fulfil specific requirements when visual inspecting: their depth at the toe of the final bead on the outside of the pipe shall not exceed 0.8 mm or 12.5% of the pipe wall thickness, whichever is smaller. Moreover, there must not be more than 50 mm of undercutting in any continuous 300 mm length of weld. In addition to these requirements, depth of undercuts found in the cover or root bead shall not be larger than values given in Table 6, when inspection is carried out visually or by mechanical means.

Table 6: Limits for undercut depth and length in API 1104 [24].

Depth	Length
$D > 0.8$ mm or $D > 0.125\,t$, whichever is smaller	Not acceptable
0.4 mm $< D \leq 0.8$ mm or $0.06\,t < D \leq 0.125\,t$, whichever is smaller	50 mm in a continuous 300 mm weld length or one-sixth the weld length, whichever is smaller
$D \leq 0.4$ mm or $D \leq 0.06\,t$, whichever is smaller	Acceptable, regardless of length

Alternative acceptance criteria for girth welds are provided in this standard, following an engineering critical assessment (ECA). However, when pipelines are subjected to cyclic loads and significant crack growth is expected to occur, the user is referred to validated fitness-for-purpose assessment methods [3], in order to establish acceptance limits for defects.

2.8. Det Norske Veritas-Germanischer Lloyd, DNVGL RP-C203 [25]

This recommended practice should be applied to high cyclically loaded structures made of carbon-manganese steel with yield strength below 960 MPa. It emphasises that offshore structures can withstand significant amount of cycles ($N \geq 10^7$), and therefore, it recognises the importance of a reliable assessment in the high cycle fatigue regime. With regard to undercuts, it is recommended to construct a proper WPS to avoid deep undercuts in production. Common workmanship standards are considered in design S-N curves, and default tolerance for this type of imperfection is normally limited to 0.6 mm [26]. However, specific requirements can be assigned depending on the desired fatigue strength. Tolerances for undercuts are then limited to null for S-N curves better than D, 0.5 mm for classes F to D, and 1 mm for class F1 and lower. In the case of butt welds with desired fatigue behaviour better than class D, ISO level B125 applies [2]. For defects with tolerances exceeding those limits, assessment should be supported with proper fracture mechanics calculations [3, 27].

3. Comparison of normative documents

In order to compare predictions with acceptance limits for undercut at the toe of welded connections in current regulations, it is important to mention that the best parameter to do this is undercut depth, D. It can be found in literature, and it is summarised in [1], that this measure provided the best description of experimental results, disregarding other undercut dimensions, like root radius, width or length. Petershagen [10] chose the parameter D/t since it is non-dimensional and it was preferred in old codes of practices. He additionally suggested that it was able to account for a slight decrease in fatigue strength with increasing plate thickness, for a constant value of D/t. Iida et al. [28] also proposed acceptance levels for undercut depth in terms of that ratio.

From the documents described in previous section, IIW, VOLVO, BS and ISO establish tolerances for undercuts in terms of D/t, and consider a maximum depth that cannot be exceeded. The rest of the codes and standards set acceptance limits based only on undercut depth, without considering thickness. Additionally, some documents demand requirements in terms of undercut length [19, 24] and others distinguish between different types of joints and loading directions. Moreover, VOLVO presents special requirements for weld toe radius [15], which differs from ISO 5817, BS and IIW that solely request a smooth transition between the weld and the base material. Table 8 summarises acceptance limits in aforementioned documents for undercuts under cyclic loading, in terms of parameter D/t and maximum permissible depth, $D_{\max}$. Fatigue class corresponding to each weld designation or quality system, is displayed in column two. Additionally, equivalent FAT values are provided, based on design S-N curves from each document.

Table 7: Undercut tolerances in codes and standards for butt-welded joints under fatigue loading.

Document	Fatigue class denomination	FAT	Tolerance	
			D / t	D_{max} [mm]
IIW Guidelines [5]	FAT 100	100	0.025	1
	FAT 90	90	0.05	1
	FAT 80	80	0.075	1
	FAT 71 and lower	71	0.1	1
SS-EN ISO 5817 [1]	B125	125	0	0
	B90	90	0.05	0.5
	C63	63	0.1	0.5
BS 7608 [12]	C	125	0	0
	D	90	0.025	1
	E	80	0.05	1
	F	71	0.075	1
	F2 and lower	63	0.1	1
VOLVO STD 181-0004 [15]	VB	125	0	0
	VC	100	0.04	1
	VD	80	0.05	1
	VE	63	0.1	1
AWS D1.1 [19]	C	90	-	0.25
ASME BPVC Sec. III [24]	C	90	0.1	0.8
API 1104 [25]	-	-	0.06	0.4
DNVGL RP-C203 [26]	C2	100	-	0
	D	90	-	0.5
	E	80	-	0.5
	F	71	-	0.5
	F1 and lower	63	-	1

Some documents assign different tolerances to different desired fatigue strength [2, 8, 13, 15, 25], but others do not consider alternative levels of conservatism [19, 21-24]. As it is expected, codes of construction like AWS and ASME adopt the most conservative values. In the former case, it has limited undercut depth to 0.25 mm for several years without any strength consideration. Tolerances for undercuts in API 1104 are also based on empirical criteria for good workmanship. Although these limits have proven to be reliable in pipeline systems throughout the years, if a more stringent analysis is desired, fitness-for-purpose assessment can be used [3]. High cycle fatigue considerations are lightly accounted for in this standard, and it is not clear whether tolerances are defined for static or cyclic loading conditions. In spite of this, limit values adopted throughout the document are useful for comparing with other standards and codes.

In the following section, fracture mechanics based methodology employed to predict fatigue strength of welded joints containing undercuts is described, and previous results from the authors are discussed. Further analyses and comparison with norms are additionally presented.

4. Fracture mechanics approach

The use of fracture mechanics in regulations allowed the application of different methodologies to estimate the remaining fatigue life of welded components containing defects. FFP methods have been included in many documents and they provide additional support to rejection or acceptance of a particular flaw. This assessment is generally based on remaining fatigue life and damage-tolerant considerations, and it should be supplemented with a proper inspection and maintenance programme. It is relevant when safe-life assessment is economically unfavourable due to enhanced requirements, or when some damage can be justified by structural conditions. The fracture mechanics approach developed in the present paper is applied to welded components containing undercuts to predict their fatigue strength. The latter is a suitable parameter to set acceptance limits for undercut depths in welded structures, and it can therefore be applied to fatigue design.

4.1. Methodology

Methodology employed in the present work is extensively described in previous publications from the authors [1, 29-31]. The fracture mechanics resistance curve method is applied to define fatigue endurances for different weld configurations. This tool is widely used in literature to assess fatigue behaviour, especially in the short crack regime [32-37]. By comparing the total driving force applied to a crack with its threshold for propagation, ΔK_{th}, the effective driving force is obtained. The latter is the energy necessary for crack propagation.

The applied driving force is a function of crack length and it is properly described by the applied stress intensity factor range, ΔK. Likewise, threshold depends on crack size and it includes the short crack regime in the present approach. Relationship between these quantities can be expressed as a modified Paris Law, like Eq. (1).

$$da/dN = C\,(\Delta K - \Delta K_{th})^{m} \qquad (1)$$

where C and m are constants that depend on material and environment. It was found [38, 39], that Eq. (1) better describes short crack growth behaviour than other variants. Note that in the case of fatigue endurance assessment, values adopted by constants in Eq. (1) is irrelevant, since for da/dN approaching to zero only equality between ΔK and ΔK_{th} defines the limiting or critical stress range.

Once threshold and stress intensity factor curves are defined, comparison can be done as indicated in Figure 1, for three different values of the nominal stress, $\Delta\sigma_N$. It should be pointed out that there is a single value of $\Delta\sigma_N$, for which both curves touch at a single point (i.e. they are tangent). Corresponding value of stress is the fatigue endurance of the specific weld configuration, $\Delta\sigma_e$, and the abscissa indicates the non-propagating crack length,

a_{np} (straight arrow). When $\Delta\sigma_N$ is higher than the fatigue limit, then there is no contact between the curves, and crack propagation is possible for every value of initial crack length. On the other hand, when $\Delta\sigma_N$ is lower than the fatigue limit, curves intersect at a particular crack length (dotted arrow), above which crack growth is favoured. The presence of cracks with length below that value is not accompanied by crack propagation.

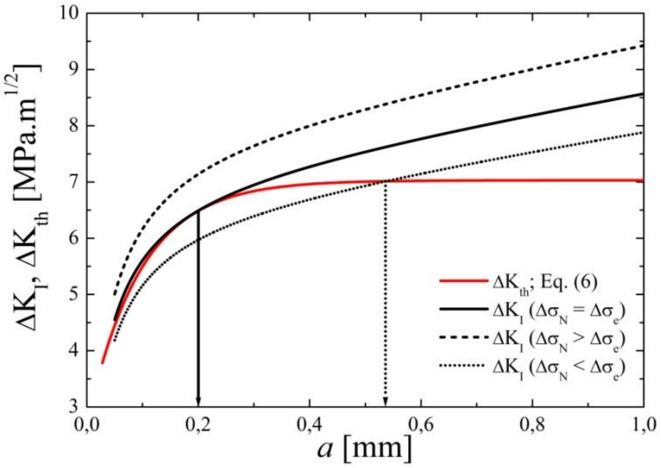

Figure 1: Schematic view of the resistance curve methodology, for three different values of nominal stress, $\Delta\sigma_N$.

4.2. Determination of fatigue crack propagation threshold

Chapetti proposed a method to calculate crack propagation threshold [36] that differs from those found in literature [32-34]. He suggested that location d of the strongest microstructural barrier defines a microstructural threshold for short crack propagation, as follows:

$$\Delta K_{dR} = Y\Delta\sigma_{eR}\sqrt{\pi d} \qquad (2)$$

where Y is a geometrical factor and $\Delta\sigma_{eR}$ is the plain fatigue limit, described as the nominal stress range below which cracks would not propagate in a smooth sample. Its value depends on the stress ratio, R, and therefore, the microstructural fatigue threshold also does. Definition of ΔK_{dR} as a function of the length of the strongest microstructural barrier is well supported in literature [33, 40-42].

In the case of long cracks, threshold adopts a constant value, represented by ΔK_{thR}, for a given stress ratio R. Difference between this mechanical threshold for long cracks and microstructural fatigue threshold, ΔK_{dR}, gives ΔK_{CR}, as shown in Eq. (3).

$$\Delta K_{CR} = \Delta K_{thR} - \Delta K_{dR} \qquad (3)$$

where ΔK_{CR} is constant and depends on the stress ratio R. In order to shift from ΔK_{dR} to ΔK_{thR} a transition region should be considered. Chapetti suggested [36] that the development of the extrinsic component ΔK_C can be calculated with Eq. (4).

$$\Delta K_C = \Delta K_{CR}\left(1 - e^{-k(a-d)}\right) \quad (4)$$

where k is a material constant that controls the shape of the transition zone for each stress ratio, and a is the crack length in mm, measured from the free surface. A similar expression was employed by McEvily and Minakawa in their studies of crack closure development [32], but variables involved differ from those presented in Eqs. (3) and (4). Further discussion about differences between available models to estimate ΔK_{th} can be found in [43].

Finally, the shape of a single threshold curve that describes the resistance of a material to crack propagation from a size d can be described by Eq. (5).

$$\Delta K_{th} = \Delta K_{dR} + \Delta K_C = Y \Delta\sigma_{th}\sqrt{\pi a} \quad (5)$$

By replacing Eqs. (3) and (4) into (5), the following form of the threshold curve can be obtained:

$$\Delta K_{th} = \Delta K_{dR} + (\Delta K_{thR} - \Delta K_{dR})\left(1 - e^{-k(a-d)}\right) \quad (6)$$

which is valid for $a \geq d$.

Studies carried out by Chapetti showed that the value of k in Eq. (7) gives a threshold for fatigue crack propagation in good agreement with experimental data [36].

$$k = \Delta K_{dR}/[4d(\Delta K_{thR} - \Delta K_{dR})] \quad (7)$$

In order to determine the fatigue limit of a specific weld configuration at a particular value of R, the applied stress intensity factor as a function of crack length must be known. This is generally achieved by means of finite element analyses [1]. Then, after assuming that Eq. (1) governs fatigue crack growth, fatigue limit can be simply obtained by equalising ΔK to ΔK_{th}, no matter the value for the exponent m and the constant C. This process is illustrated in Figure 1.

4.3. Prediction of fatigue strengths

In previous works, the authors applied this methodology to a 19 mm butt-welded joint containing undercuts along the whole length of the weld bead, and loaded under four point bending (4PB) [1]. Reinforcement angle was set to 147° and undercut dimension was varied parametrically in order to obtain different stress concentration factors at the root of the notch, for different undercut depths. The analysis was purely geometric and residual stresses resulting from the welding process were not considered. Overall geometry and symmetric model employed for the assessment are displayed in Figure 2a. Load configuration and boundary conditions are also shown. Half minor and major span are represented by s and L, respectively, t is the plate thickness, α is the reinforcement angle and P is the applied load. All these variables define the maximum nominal stress on the surface that is used in the calculations. Figure 2b schematically illustrates an undercut with its most important dimensions and the stress distribution generated by the notch.

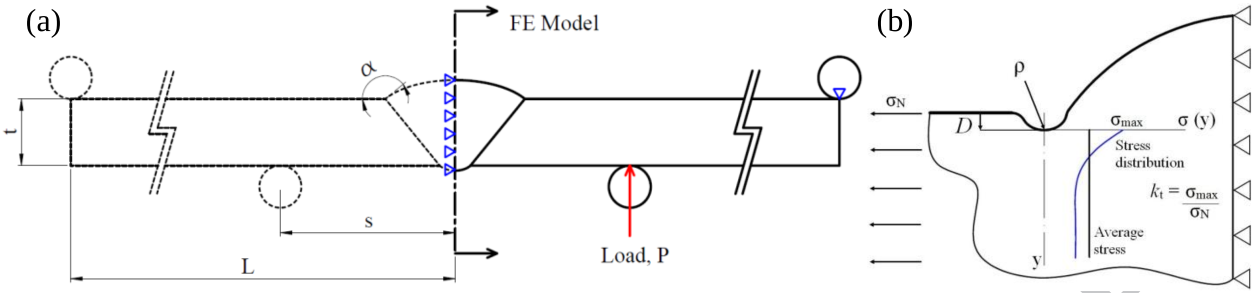

Figure 2: (a) Geometry, load configuration and boundary conditions of the finite element model and (b) schematic representation of an undercut at the toe of the weld.

The study made use of a scientific based methodology to assess the influence of different geometrical variables, and it concluded that undercut depth better describes undercut influence, rather than undercut radius, length, or width. This contradicts previous researches found in literature which are either empirical or based on continuum mechanics that solely employ the stress concentration factor to analyse undercut influence on fatigue strength. Figure 3 illustrates results from the aforementioned study in the form of a Frost diagram. Proposed fatigue strengths for each undercut depth are shown with broken horizontal lines. Detailed explanation about how these results were obtained can be found in reference [1], together with further discussions about the influence of undercut geometry on fatigue strength.

The aim of the present work is to extend the assessment in order to compare predictions directly with acceptance limits employed in industry and engineering. In general, they are related to a design S-N curve, which is normally based on extensive experimental data of real welds, and hence they include residual stresses, angular misalignment, thickness effects and other loading modes in their definition. Consequently, methodology must now consider all these factors to establish a direct comparison with FAT values usually mentioned in design regulations.

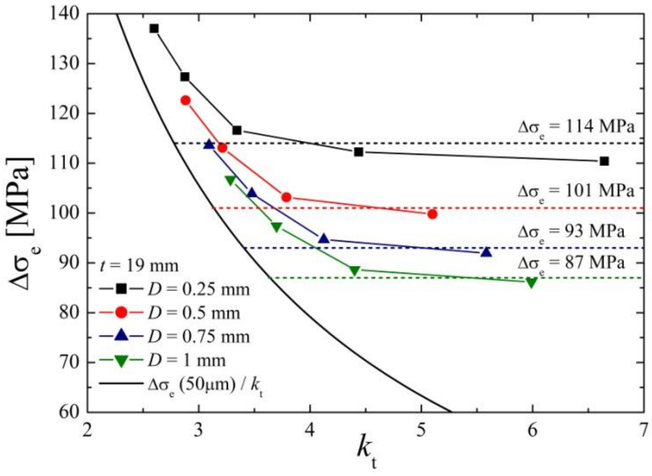

Figure 3: Predicted fatigue strengths for different undercut configurations. A36 steel, a_i = 50 µm, R = 0.1 [1].

4.4. Thickness and loading mode

If the loading mode is traction, the load in Figure 2 should be located at the end of the sample, parallel to the plate plane. Results for this loading scheme can be seen with broken lines in Figure 4a. Note that fatigue strengths under traction are comparable to those corresponding to 4PB.

The same procedure carried out for a 19 mm butt weld [1] can be applied to other thicknesses. Then, proposed fatigue strengths for each undercut depth (shown with broken horizontal lines in Figure 3) can be plotted against the ratio of each undercut depth and corresponding thickness, D/t. Figure 4b presents these results in A36 butt welds for several thicknesses, under 4PB and traction at $R = 0.1$. It can be noted that curves corresponding to D = constant, can also be drawn, showing an increase in fatigue strength with decreasing thickness. This kind of curves can be useful to assess maximum permissible undercut depth, according to most documents described above.

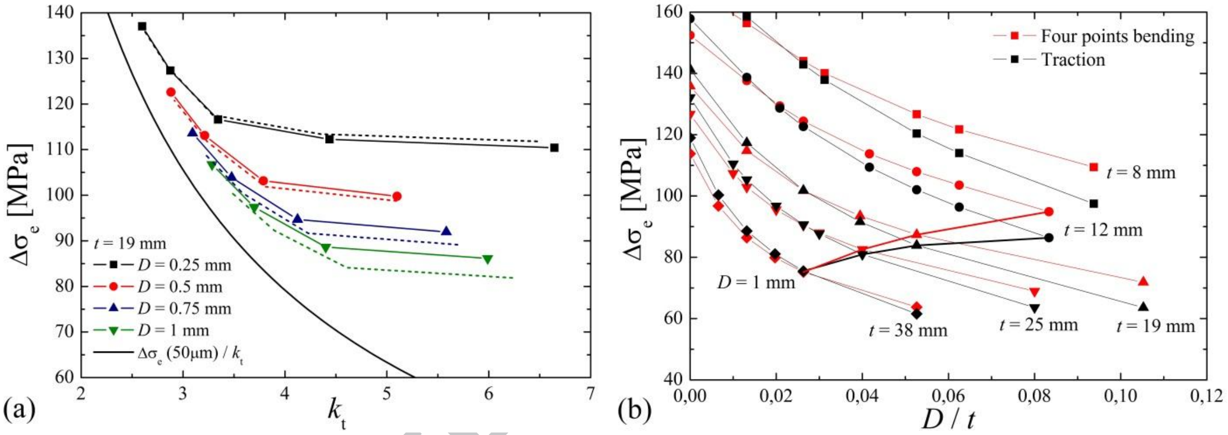

Figure 4: Influence of (a) loading mode and (b) thickness on the fatigue strength of welds with undercuts. A36, a_i = 50 µm, R = 0.1.

4.5. Residual stress correction

In order to unify criteria in curves from Figures 3 and 4 and tolerances from regulations, residual stresses must be considered in the fracture mechanics approach. This can be done by analysing the change in the resistance curve for different values of stress ratio, R. As an example, a weld 25 mm thick without undercuts and under traction was used. Resistance curve and critical condition in stress-relieved A36 steel is shown with dark lines in Figure 5. To assess the effect of residual stresses, dependence on the stress ratio of both the long crack propagation threshold, ΔK_{thR}, and the plain fatigue limit, $\Delta\sigma_{eR}$, must be known. In the former case, it was found [31] that the following relation applies to A36 steel, for ΔK_{thR} in MPa· m$^{1/2}$:

$$\Delta K_{thR} = 7.6 - 5.7\,R \qquad (8)$$

A quick examination of Eq. (8) and Figure 5 reveals that plateau given by long crack propagation threshold, is shifted to lower values of ΔK, when R is increased. Therefore, a reduction in fatigue strength is likewise expected, because the contact point between curves takes place at lower stresses.

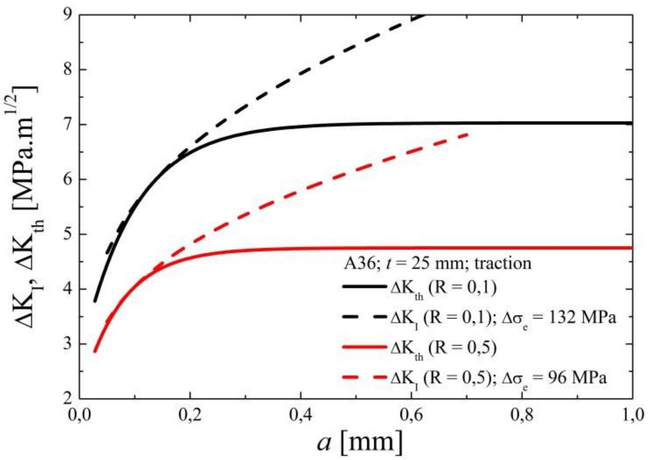

Figure 5: Variation of resistance curve and critical applied stress intensity factor in A36 butt welds, at different values of R.

On the other hand, a conservative estimation of the plain fatigue limit in the heat affected zone (HAZ) for different values of *R* can be obtained by means of Goodman´s relation. It is easy to demonstrate that Eq. (9) relates stress amplitude at *R* = -1, σ_{e-1}, with stress amplitude at a different asymmetric stress ratio, *R*, σ_{AeR}.

$$\sigma_{AeR} = 1/\{(1/\sigma_{e-1}) + (1+R)/[\sigma_{UTS}\,(1-R)]\} \quad (9)$$

σ_{UTS} is the ultimate tensile strength, estimated for the HAZ (1000 MPa) from hardness measurements.

Since the value of $\Delta\sigma_{eR}$ = 360 MPa used in predictions corresponds to *R* = 0.1 [31], then the inverse procedure should be followed to find σ_{e-1}. By doing so, it can be obtained that σ_{e-1} = 231 MPa. After this, stress amplitude for other stress ratios can be deduced directly from Eq. (9). Particularly, for *R* = 0.5, σ_{AeR} = 136 MPa, and therefore $\Delta\sigma_{AeR}$ = 272 MPa. Finally, a change in the plane fatigue limit, $\Delta\sigma_{eR}$, with *R*, produces a variation of the microstructural fatigue threshold, ΔK_{dR}, according to Eq. (2), resulting in ΔK_{dR} = 2.86 MPa√m.

Resistance curves for *R* = 0.1 and *R* = 0.5 are depicted in Figure 5. It is also indicated in this plot, the curve for the applied stress intensity factor range in the limiting condition (i.e. where it touches the threshold curve at a single point) for *R* = 0.1 and 0.5. It must be pointed out, that transition from ΔK_{dR} to ΔK_{thR} is controlled by *k* according to Eq. (6). Due to the fact that parameter *k* depends on both ΔK_{dR} and ΔK_{thR} (see Eq. (7)), it´s value, and consequently the shape of the transition region, are also affected by changes in R.

It is worth mentioning that an initial crack length of 50 μm was employed in all calculations. However, it can be seen in Figure 5 and also in reference [1] that the fatigue limit of welds containing sharp notches (high k_t) is determined by the non-propagating crack length. This quantity is found to be over 200 μm in the presence of undercuts, and hence it overshadows the influence of a_i on fatigue strength predictions.

4.6. Angular and linear misalignment

The effect of misalignment in axially loaded joints can be quantified due to the occurrence of secondary shell bending stresses that leads to an increase of stress in the weld. It must be mentioned that methodology described in sections 4.1 and 4.2 can also be applied to butt welds presenting linear or angular misalignment. However, in order to focus the attention on undercut effects on fatigue strength and their acceptance limits to safe fatigue design, stress magnification factor, k_m, proposed by IIW is going to be used [8]. It must be highlighted that some amount of misalignment is already included in FAT values of classified structural details. Particularly, transverse butt welds account for a misalignment of up to 10 % of wall thickness, resulting in a stress up to 30 % higher. Additional considerations must only be included when misalignment exceeds this value. Keeping this in mind, results from previous section should be affected by a factor $k_m = 1.3$, in order to account for misalignment in current prediction. Note that BS 7910 allows to $k_m = 1.34$ for quality category Q3 (FAT 71). Assessment of misalignment by means of the fracture mechanics method proposed in this article will be carried out in future studies, in order to confirm magnification factor values.

4.7. Fatigue resistance in terms of FAT values

Previous analysis gave results of fatigue limits for butt-welded joints with different thickness and several undercut configurations (see Figure 4). This means that infinite fatigue life is obtained in those welds if loaded below that stress. Although comparison of results with fatigue limits from normative documents is reasonable from a safe-life design point of view, it can be over-conservative in cases where fatigue is not the primary damage mechanism, like in nuclear reactors or oil piping systems. Moreover, even in situations where severe fatigue damage is expected, design is generally based on FAT values, with satisfactory results. Therefore, the use of FAT values is justified and they are valuable to compare tolerances in relevant regulations with results from current predictions.

In order to convert fatigue limits to FAT values, the assumption that previous results correspond to 10^7 cycles must be made. Then, relation between these two quantities can be established according to Eq. (10).

$$FAT = [(\Delta\sigma_{e,0.5}/k_m)^m \cdot 10^7/2 \cdot 10^6]^{1/m} \quad (10)$$

where $\Delta\sigma_{e,0.5}$ is the fatigue limit of the defective joint at $R = 0.5$ obtained as explained above, k_m is the correction factor for misalignment, which is 1.3 for transverse butt welds and m is the inverse slope of the S-N curve in the log-log scale, which is usually assumed as 3. By means of Eq. (10), all results from prediction can be converted to FAT values, and be directly compared to code and standard tolerances.

5. Results and discussions

Acceptance limits for undercuts expressed as a function of D/t in Table 8 are summarised in Figure 6. It shows maximum tolerances for several desired fatigue strength, in terms of FAT values. These documents are meant to be applied when fatigue is an important damage mechanism. Therefore, it is reasonable that they show a continuous decrease in fatigue strength for increasing undercut depth and constant thickness. It must be highlighted that connection between points was made by a straight line rather than a stepped profile [10], since in real structures a continuous decrease in fatigue strength is expected, for increasing undercut depths. Together with tolerances from regulations, a scatter band from literature is depicted [10, 44], corresponding to butt welds containing undercuts. Note that acceptance limits lay below the scatter band.

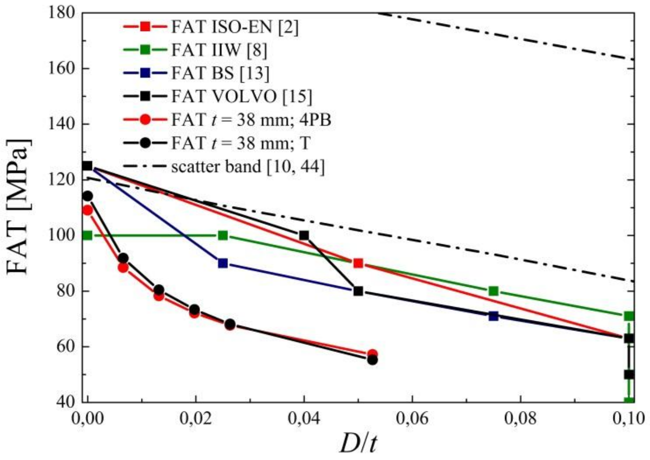

Figure 6: Predicted fatigue strengths and tolerances from regulations in terms of FAT, in A36 butt joint. a_i = 50 µm, R = 0.5.

It can be seen in Figure 6 that ISO 5817, BS 7608, VOLVO STD 181-004 and IIW recommendations follow similar trends. Together with these tolerances, predicted FAT values obtained as explained before are shown for 38 mm thick butt welds, under 4PB and traction. These curves give the FAT value of the corresponding weld when D/t = 0, and decrease continuously with undercut depth. Note that they accurately describe the trend followed by most documents. This is understandable since most of the experimental tests from which tolerances are defined in normative documents, were reported for a specific thickness, with varying undercut depth [10]. None of the documents depicted in Figure 6 allows for undercuts with D/t exceeding 0.1.

It is important to highlight that BS, ISO and VOLVO claim a FAT 125 for D/t = 0, which should be considered as the maximum FAT that can be expected in a weld containing undercuts, as the only imperfection. This must not be confused with the fatigue class assigned to the butt weld, which is generally around FAT 90.

The use of curves for t = 38 mm or higher is justified since design documents account for real welds with t generally in the range of 10 to 40 mm.

It can additionally be demonstrated that methodology proposed in the present study is able to assess variations in thickness when keeping undercut depth constant. This is relevant if the limit of D = 1 mm, normally assumed in codes and standards, needs to be defined in Figure 6. In this regard, Figure 7 illustrate curves for D = 0.5 mm [2] and D = 1 mm [8, 13, 15], by considering 4PB and traction. These curves give a safe maximum stress below which the weld can be loaded, provided that undercut depth does not exceed the value assigned to each case. The limiting condition that rules design corresponds therefore to D = 0.5 mm or D = 1 mm, and it is no longer defined by curves for t = constant. It can be seen that for high values of D/t, undercut depths below 0.5 or 1 mm result in higher fatigue strengths than tolerances proposed in regulations, proving that these documents reflect conservative values of fatigue strengths. It is also important to mention that combination of the curve for a sufficiently high thickness and the curve for $D_{\max}$ = 1 mm, assure a FAT value over ca. 70 MPa.

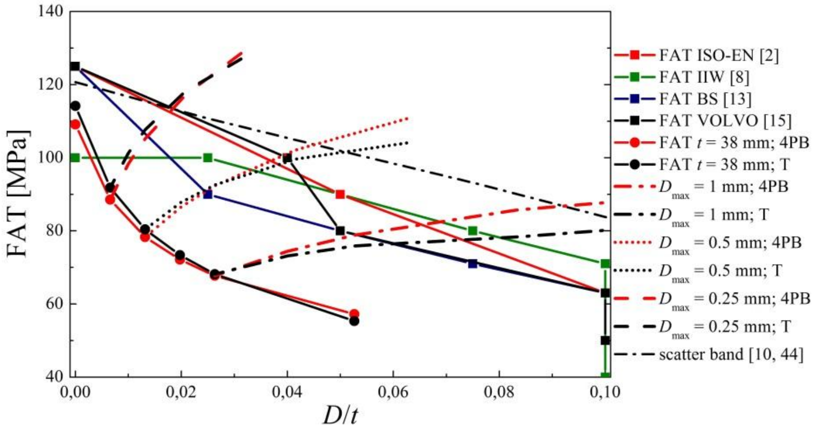

Figure 7: Predicted FAT curves for D = 0.25 mm, 0.5 mm and 1 mm. A36 butt joint, a_i = 50 µm, R = 0.5.

If maximum permissible values for D and D/t are considered (1 mm and 0.1, respectively), we can see from Figure 7 that the resulting fatigue strengths for traction and bending are comparable to the lower boundary of the scatter band (ca. FAT 85). This case corresponds to a thickness of 10 mm, which turns to be equal to the minimum thickness for which tables for undercut tolerances are valid [8, 13]. This conservatism usually included in normative documents is justified since a single parameter D/t is considered to set acceptable limits. If both D/t and D are considered in design, more permissible documents can be developed. A limiting curve for undercut tolerances should include the curve for a sufficiently high thickness (e.g. 38 mm) and a maximum undercut depth, like 1 mm. However, it is not clear in literature, whether this maximum value of D is due to safety issues or purely cosmetic.

Proposed methodology allows studying these variations of different parameters that affect the fatigue behaviour of the weld. Furthermore, it may serve as a tool to evaluate specific cases where only undercut depth is restricted. If AWS D1.1 is considered, it can be read from Table 8 that it establishes the most conservative tolerances, since no undercuts deeper than 0.25 mm are permitted. Less stringent requirements are defined by ASME, which limits undercut depth to 0.8 mm. On the other hand, API states a maximum depth of 0.4 mm, regardless of fatigue strength. All these tolerances can be analysed by observing the D = constant curves in Figure 7. For instance, curve for D = 0.25 mm lays above FAT 90 for all values of t considered in AWS ($t \geq 3$ mm). Since FAT 90 (or equivalently Category C) is assigned in the code to complete joint penetration butt welds, all undercuts that passed the inspection guarantee the integrity of the component for any thickness of the joint. However, it is proved that deeper undercuts can still achieve fatigue strength better than FAT 90, evincing the high level of conservatism assumed in this code. In general, although these documents (AWS, ASME and API) address fatigue in some clauses, they are not intended to assess fatigue behaviour, and refer to other well-known standards when high cycle fatigue is known to be relevant. Therefore, it is reasonable that they adopt high safety margins when defining tolerances.

Figures 6 and 7 are useful to describe experimental data found in literature as a function of the parameter D/t. In spite of this, it is difficult to assess individual effects of thickness and undercut depth in this kind of plot. Let´s assume a butt welded component with a desired fatigue resistance of FAT 63. From Table 8 and Figures 6 and 7, it can be seen that BS, VOLVO and ISO allow $D/t \leq 0.1$. There are infinite values of D and t for which this relation is valid; for instance, an undercut 0.8 mm deep in an 8 mm weld, or a 1 mm undercut in a 10 mm weld. These two examples have actually different fatigue strengths, which leads to different levels of conservatism, when compared to the lower fatigue strength proposed in regulations.

Additionally, outcomes for D/t = constant showed a continuous decrease in fatigue strength with increasing thickness. This effect was also suggested in literature [10, 28], based on limited experimental data and simple fracture mechanics calculations. In order to propose a safe tolerance for undercuts in terms of D/t, a sufficiently high thickness should be considered, depending on the application or industrial area where the component is in service.

Due to the difficulties exposed in previous discussion about the use of D/t as a single parameter to describe the influence of undercuts on fatigue behaviour, alternative plots relating FAT values, undercut depths and thickness can be developed. Figure 8 shows the variation of the former with respect to plate thickness, for an A36 butt weld under traction and for different values of D. Note that there is a decrease in fatigue resistance with increasing thickness, for a fixed value of undercut depth. This effect is smaller for undercuts above 1 mm and thick welds, in accordance with Petershagen´s results based on fracture mechanics [10], where only a slight effect of t was observed, for particularly deep undercuts ($0.5 \leq D \leq 3$ mm). Likewise, experimental tests in [28] also revealed a small influence of t for thick welds (30 and 40 mm). It is worth mentioning that curve for $D = 1$ mm lays close to FAT 80, which can be an explanation for the empirical restriction usually found in regulations ($D_{\max} = 1$ mm). In other words, undercuts around 1 mm deep lead to fatigue strengths approximately equal to a low fatigue class of a butt weld (FAT 80).

If acceptance limits from normative documents as a function of D/t are considered, curves for D = constant show an increase in FAT values for increasing thickness. Particularly, the curve resulting from setting $D = 1$ mm in IIW recommendations [8] is plotted with broken line in Figure 8, and it follows a different trend than exposed results. The reason for this discrepancy is that standards do not account for an increase in fatigue strength when thickness is reduced. This can lead to very conservative tolerances for small thicknesses. Moreover, these differences between results and regulations evince the inability of D/t as a single parameter to describe the whole fatigue behaviour of a defective weld.

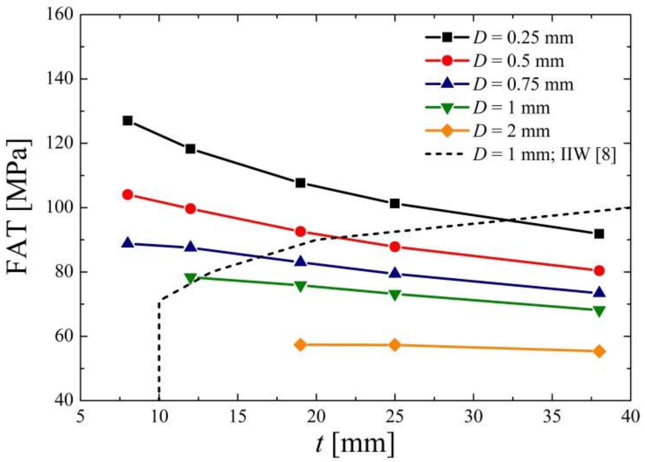

Figure 8: FAT curves for constant undercut depth as a function of *t*, in A36 butt welds under traction. a_i = 50 µm, *R* = 0.5.

Similar assessment can be performed as a function of undercut depth, as illustrated in Figure 9. If this chart is compared with Figure 4b, it can be seen that curves are closer in the former. This observation partly explain suggestions from [10] and [28], where no noticeable effect of thickness could be appreciated when using *D* in the abscisas.

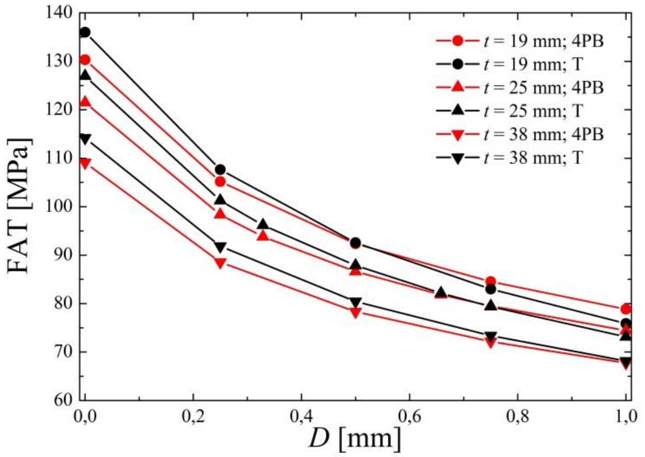

Figure 9: Predicted FAT curves as a function of *D* in A36 butt welds. a_i = 50 µm, *R* = 0.5.

Figure 9 can be used to compare tolerances in industry for a specific thickness. Figures 10a and 10b correspond to restrictions in undercut depth, for 19 mm and 25 mm butt welds, respectively. Note that tolerances were drawn with stepped curves to highlight differences between documents. DNVGL RP-C203, BS 7608, VOLVO STD 181-004 and IIW recommendations limit maximum tolerable undercut to 1 mm, for any thickness. In the 19 mm joint, ISO 5817 follows a similar trend to BS up to 0.5 mm, which is the maximum acceptable depth, imposed by this standard for this kind of weld. DNVGL presents less conservative strength than ISO beyond *D* = 0.5 mm, but it is more conservative than BS, IIW and VOLVO. In this regard, the latter establishes the least conservative tolerances up to D = 0.8 mm, above which IIW becomes less conservative. It must be considered that VOLVO demands additional requirements in terms of undercut radius, which may allow to less stringent tolerances than those from its counterparts. Author´s predictions for four point bending and traction are also displayed in Figure 10. Note that they accurately describe the trend followed by most documents. In the case of shallow undercuts ($D < 0.25$ mm), predicted values are less conservative than codes and standards, but it should be considered that BS, ISO and VOLVO claims a FAT 125 for $D = 0$, which is very close to current predictions for $t = 25$ mm.

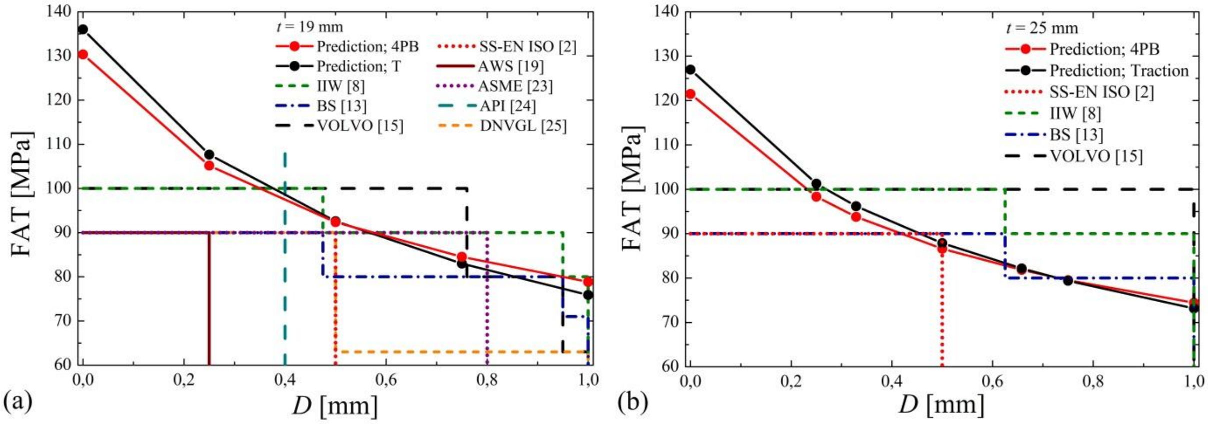

Figure 10: Predicted FAT curves for (a) *t* = 19 mm and (b) *t* = 25 mm, and tolerances from regulations, as a function of *D*.

Previous comparison between current predictions and tolerances in codes, standards and recommendations suggests that D/t accurately describes the trend in experimental results, and it can be used as a lower boundary to undercut acceptance limits. It was demonstrated here that the ability of this parameter to assess fatigue behaviour is related to the fact that most of experimental data in literature is obtained for a constant thickness; undercut dimensions are changed and results are reported for that specific thickness. However, if both variables D and t are rigorously accounted for, as depicted in Figures 8 and 9, it was proved that D/t by itself cannot describe general behaviour of the joint. This ratio seems to hide individual effects of undercut depth and thickness, which can be significant under certain circumstances. Alternatively, undercut depth can be used.

A final analysis can be carried out, by considering previous discussion. A plot relating undercut depth and thickness can be made, in order to obtain safe regions for these dimensions, as it was proposed in [28]. In this study, the authors recommended acceptance limits for undercut depth in power plant components based on a fatigue strength reduction of 20% that accounted for the resistance of the weld without undercuts and that containing defects. This reduction was associated to $D/t = 0.02$, which is represented by a slope in Figure 11. Note that IIW [8] proposes a FAT 100 for $D/t = 0.025$ with $D_{max} = 1$ mm (see Table 1). Hence, this case can be described by a similar curve in Figure 11.

Results from current predictions are also displayed in Figure 11, for different expected fatigue strengths (FAT 80, FAT 90 and FAT 100). A clear difference can be seen between results and proposal from [28]. This discrepancy is attributed to the fact that they did not consider the effect of thickness when calculating the R_f factor, defined in their study as the ratio between the fatigue strength of the weld with undercut to the fatigue strength of a flawless weld. Further analyses are necessary to assess the importance of charts like Figure 11, but at this first instance it can be highlighted that there is a safety locus containing different combinations of *t* and *D*, for which fatigue resistance is better than a specific value of FAT. Set of data laying above these curves for constant FAT, results in lower fatigue strengths, and should not be accepted.

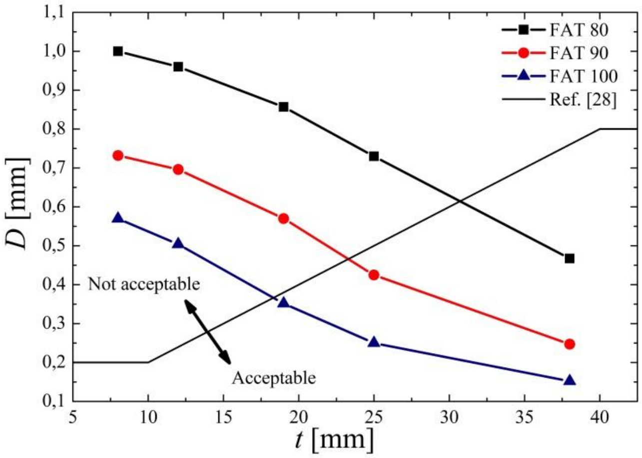

Figure 11: Proposed acceptance limits for undercut depth, for different thickness and desired fatigue performance.

Exposed analysis verifies that predicted FAT trends are in accordance with most of current regulations that consider fatigue. Some differences arise when analysing individual effects of undercut depth or plate thickness. A conservative approach for tolerance determination in industry was developed and it was shown that it can be systematically applied to account for all involved parameters.

6. Conclusions

A fracture mechanics based approach that employs the resistance curve method was used to predict fatigue limit of welded components containing undercuts. Fatigue strengths for different undercut depths were obtained for sufficiently high stress concentration factors, which leads to conservative results, since in real welds these very sharp notches are unlikely. Methodology proved to be a useful tool to quantify the effect of different variables, like defect dimensions, main plate thickness, load scheme and residual stresses. Consequently, parametric studies can be developed to compare the relative importance of involved factors. Less meaningful variables can be simplified, focusing the attention to significant parameters. In this regard, it was demonstrated that the ratio of undercut depth to thickness can adequately describe experimental data found in literature. However, it hides individual effects of *D* and *t*, which can be important under some circumstances.

Results from predictions were compared with tolerances adopted in current regulation for undercuts and good correlation was observed based on FAT values. In general, acceptance limits decrease when expected fatigue strength is higher. This trend is properly described by outcomes obtained, and the majority of standard tolerances lay above predictions for t = 38 mm. On the other hand, codes like AWS demonstrated to be very conservative.

This conservatism is justified since they are meant to safely satisfy urgent needs from the industry, combining economic issues, serviceability, ease to implementation and experience. However, cost reduction due to less demanding inspection is feasible from a fatigue performance point of view.

The use of D/t as the limiting parameter to set tolerances in industry is reasonable if a sufficiently high thickness is considered, since safe fatigue performance is guaranteed for thinner joints. In spite of this, at high values of D/t, restriction imposed by a maximum undercut depth becomes more important and it determines the limiting condition. Therefore, it is demonstrated that a single parameter is not enough to ensure safe behaviour of a weld. Relevant documents that assess fatigue usually set tolerances as a function of D/t but they also define a maximum tolerable depth. Current methodology was able to explain these facts, and also suggested a possible explanation for the limiting value of 1 mm in D, normally used in regulations.

Correspondence of FAT values with predictions based on the resistance curve concept is promising, and it is expected that this can contribute to setting reasonable and less conservative acceptance limits to weld defects in industry.

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HIGHLIGHTS

- Conservative fatigue strengths of flawed welds with residual stresses were predicted
- Undercut tolerances in norms and trend in terms of FAT values were explained
- Effect of thickness on welds containing undercuts was established
- *D*/*t* is not able by itself to assess fatigue behaviour of defective welds
- Acceptance limits for undercuts are proposed based on *D* and *t*