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Review of the Definition of Weld Penetration, Depth of Fusion and Throat Thickness on Fillet Welds

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Highlights

- This study compares the definitions of weld penetration and fusion in the standards.
- Definitions and evaluations are always made in terms of unit of length in the standards.
- Evaluation of fusion or penetration rate should be determined in terms of unit of area.

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Fop rate

Abstract

In this study, definitions of Weld Penetration (WP), Depth of Fusion (DOF) and Throat Thickness (TT) in fillet welds according to related standards are evaluated. Each standard makes its own definition related to WP, DOF and TT. Moreover, when looking at these standards, it is seen that definitions are always made in terms of unit of length. In many studies, assessment of fusion or penetration (FOP) rate on fillet welds is performed as the ratio of the maximum FOP depth to the material thickness. Depth assessment taking into consideration unit of length is not ideal for accurate evaluation of FOP rates especially on fillet welds. In the evaluation made in terms of unit of length, FOP rate can be approximately 50 percent more than the evaluation made in terms of unit of area. Method taking into consideration unit of area will be more suitable as it allows accurate assessment of FOP rates in welded joints. In this review, in addition to evaluation of the definitions of standards, it is also suggested that the evaluation of FOP rate on fillet welds should be determined in terms of unit of area rather than length.

1. INTRODUCTION

In this study, it is aimed to define how the definitions of WP, DOF and TT are made according to the relevant standards, and the similarities and differences of the definitions of standards are presented. Each standard such as AWS A3.0, ISO2553, EN 1993-1-8 and DIN EN ISO 17659 makes its own definition and demonstrates on the figures how to measure and evaluation each of WP, DOF and TT. In these standards, it is seen that the unit of length is taken into account instead of unit of area to evaluate these definitions. In this case, inaccurate results about FOP rate assessment can be obtained. Therefore, the assessment method taking into consideration unit of area is suggested in section 2.

In welded structures, WP, DOF and TT are significant weld dimensions in terms of weld quality and strength of the structure [1]. The importance of this is mentioned in many standards, welding handbooks and documents [2-7]. ISO 5817:2014 [2] standard defines the dimensions of typical imperfections and offers them in three different quality classes. This standard does not directly refer to the evaluation of WP, DOF and TT. However, it provides for the evaluation of imperfections that affect the dimensional quality of WP, DOF and TT, such as excess weld metal, excessive convexity, according to wall thickness and weld seam width. The AWS D1.1/D1.1M:2020 [3] describes some definitions for weld design as well as cites to standards such as ANSI/AISC 360 for the design of Statically Loaded Tubular Connections. It defines the required size calculation by taking into account the connection angles related to the effective throat. Within this scope, this standard emphasizes some situations, such as when the angle between 2 elements is greater than 105 degrees, the effective throat is more important than the leg length (size) for the strength of the structure. The AASHTO/AWS D1.5M/D1.5:2010 [4] states that the welded connections shall be designed and detailed to satisfy the strength, stiffness, flexibility, and fatigue requirements. In addition, some

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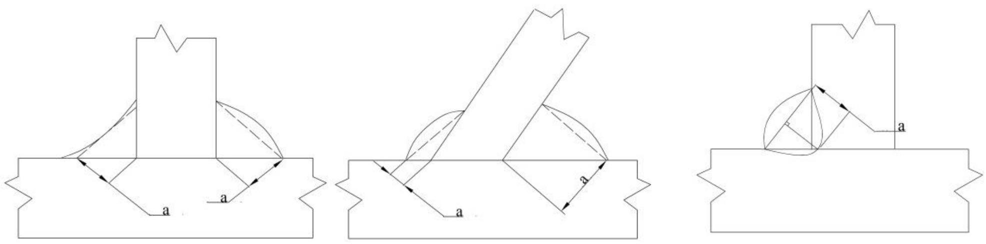
definitions of weld dimension, such as the minimum effective weld size, are also given in this standard. The minimum and maximum weld dimensions according to the joint type are given in figures and tables. The ASM Handbook [5] provides a wide range of information on welding technology. In addition to making definitions about WP, DOF and TT, it also gives recommendations on the ratio of depth to width. ASM Handbook presents the ratio of depth to width values in the relevant tables for special joining such as high vacuum partial penetration welds in thin sections. EN 1090-2:2019 [6] defines the technical requirements for steel structures. Moreover, it specifies the minimum required throat thickness with a formula based on the weld thickness for fillet welds. EN 1993-1-8:2005 [7] presents the some formulas for weld and throat thickness depending on the wall thickness or weld width, as well as what the weld length should be taking into account the wall thickness or throat thickness. Beyond the above standards, this standard formulates what should be the minimum weld length for a fillet weld, taking into account the throat thickness. It is recommended that the dimensions of fillet weld less than this value to be calculated should not carry a load. In EN 1993-1-8:2005, AWS A3.0:2010, ISO 2553:2019 and DIN EN ISO 17659:2004, WP, DOF or TT terms are defined and shown in figures.

In EN 1993-1-8:2005 [7], instead of WP term, full penetration and partial penetration are defined and demonstrated for butt welds. Full penetration butt weld is defined as a weld that has complete penetration and fusion of weld and parent metal throughout the thickness of the joint. Partial penetration butt weld is defined as a weld that has joint penetration which is less than the full thickness of the parent material. Apart from these terms, TT is defined for fillet weld and deep penetration fillet weld. In this standard, TT "a" is defined as the height of the largest triangle that can be inscribed within the fusion faces and the weld surface, measured perpendicular to the outer side of this triangle. TT for fillet weld and deep penetration fillet weld is shown in Figure 1 respectively. Effective full penetration for T-butt welds is defined in this standard, as shown in Figure 2. This standard makes an important statement that allows to determine what the minimum values "anom1, anom2 and cnom" should be.



(a) (b)

Figure 1. *TT according to EN 1993-1-8; (a) TT of fillet weld, (b) TT of deep pen. fillet weld [7]*

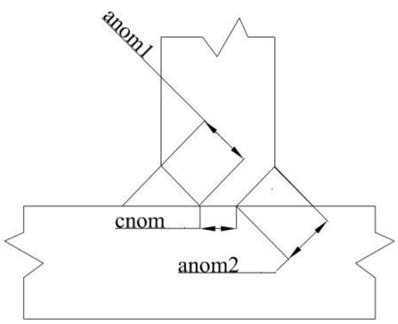
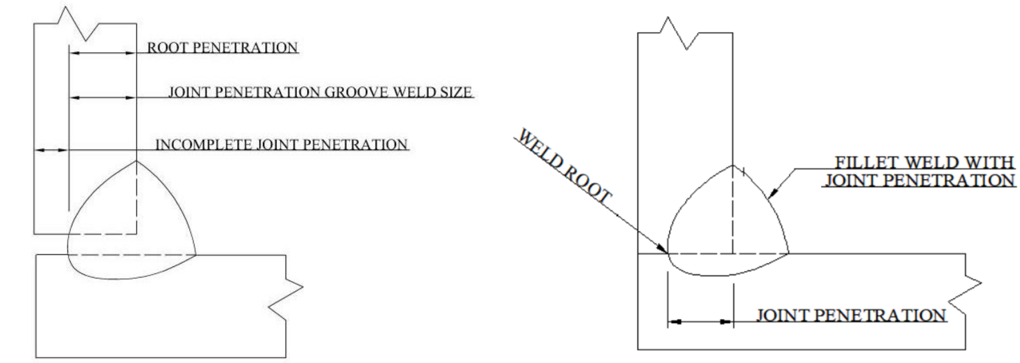


Figure 2. *Effective full penetration according to EN 1993-1-8 [7]*

In AWS A3.0:2010 [8], instead of WP term, root penetration and joint penetration are defined and demonstrated. While root penetration is defined as distance the weld metal extends into the joint root, joint penetration is defined as distance the weld metal extends from the weld face into a joint. Root and joint penetration is shown in Figure 3 as demonstrated in AWS A3.0. In this standard, DOF is also defined as distance that fusion extends into the base metal or previous bead from the surface melted during welding. DOF is shown in Figure 4. TT is defined as three ways; actual throat, effective throat and theoretical throat. Actual throat is defined as shortest distance between the weld root and the face of a fillet weld. Effective throat is defined as minimum distance from the fillet weld face, minus any convexity, and the weld root. Theoretical throat is defined as distance from the beginning of the joint root perpendicular to the hypotenuse of the largest right triangle that can be inscribed within the cross section of fillet weld. Actual, effective and theoretical throat are shown in Figure 5, respectively. Moreover, in this standard, these throat terms are explained according to convex and concave fillet welds separately.



(a) (b)

Figure 3. *Root and joint penetration according to AWS A3.0; (a) root penetration, (b) joint penetration [8]*

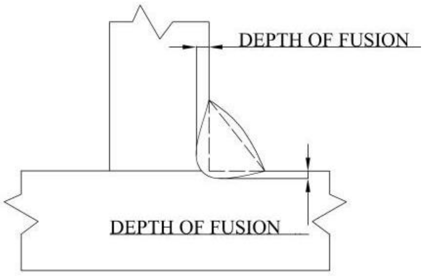
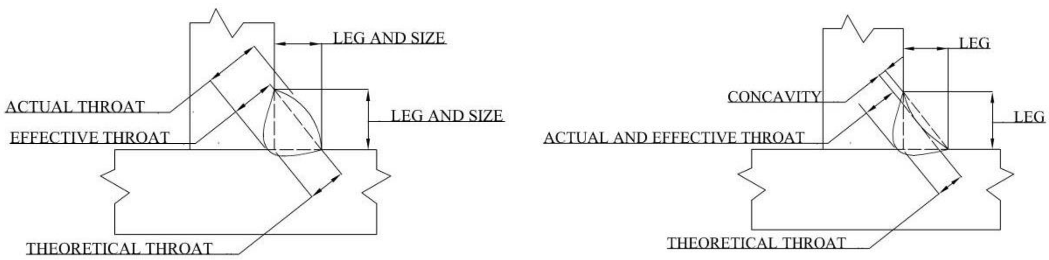


Figure 4. *DOF according to AWS A3.0 [8]*



(a) (b)

Figure 5. *TT according to AWS A3.0; (a) convex fillet welds, (b) concave fillet welds [8]*

In ISO 2553:2019 [9], penetration depth is defined as thickness of the weld metal and presented as full and partial penetration. This term is used for only butt welds in this standard. However, when looking at Table 6 (No 1.2) in ISO 2553, it is seen that this term is also used for T joint shown in Figure 6. No definition of DOF has been made in this standard. For fillet welds, TT is defined as nominal TT and deep penetration TT separately. Nominal TT “a” is defined as design value of the height of the largest isosceles triangle that can be inscribed in the section of a fillet weld. Deep penetration TT “s” is defined as nominal TT or effective TT to which a certain amount of fusion penetration is added. Z is the distance from the actual or projected intersection of the fusion faces and the toe of a fillet weld. Nominal TT and deep penetration TT are shown in Figure 7, respectively.

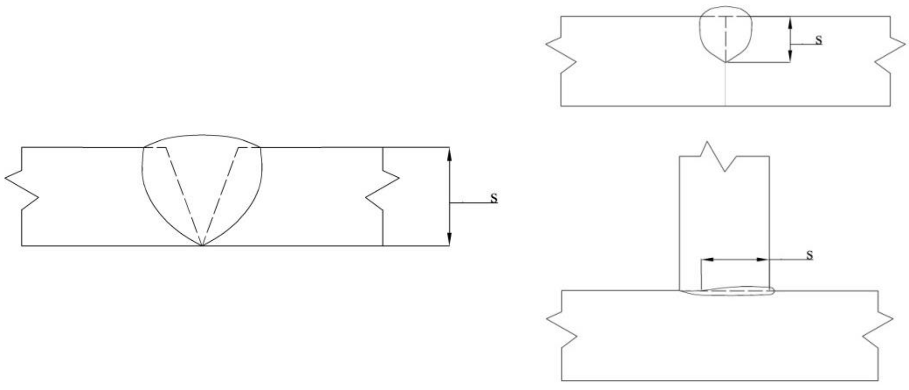


Figure 6. *Penetration depth for full and partial penetration according to ISO 2553; (a) full penetration, (b) partial penetration [9]*

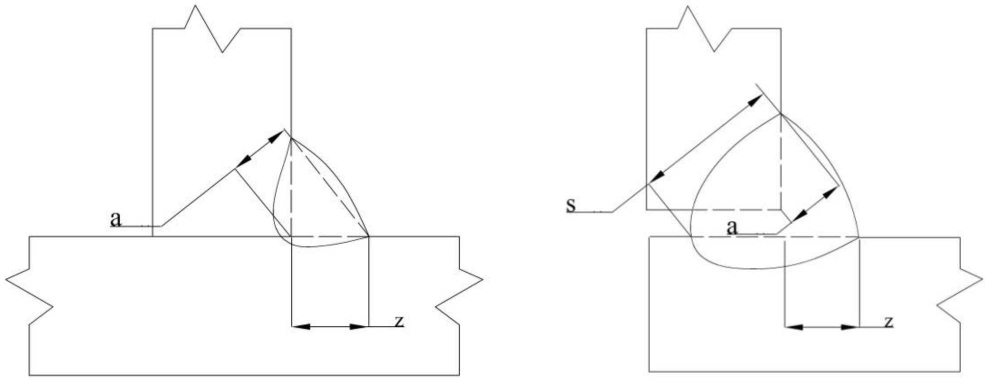


Figure 7. *TT according to ISO 2553; (a) nominal TT, (b) deep penetration TT [9]*

In DIN EN ISO 17659:2004 [10], WP, DOF and TT are only explained by the figure and no written explanation is available. Instead of WP term, fusion and root penetration are defined as shown in Figure 8. TT is defined as four ways; effective, actual, design and maximum TT as shown Figure 9.

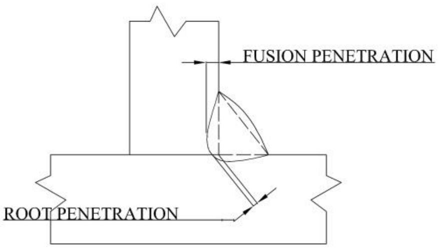


Figure 8. *Fusion and root penetration according to DIN EN ISO 17659 [10]*

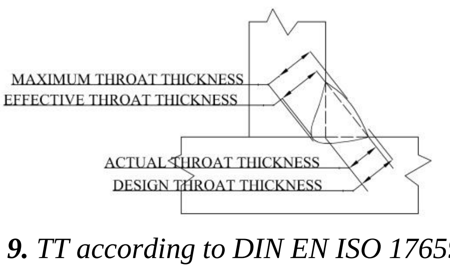


Figure 9. *TT according to DIN EN ISO 17659 [10]*

According to EN 1993-1-8, AWS A3.0, ISO 2553 and DIN EN ISO 17659, each standard has its own term and definition. All terms and definitions related to WP, DOF and TT are summarized in Table 1 below.

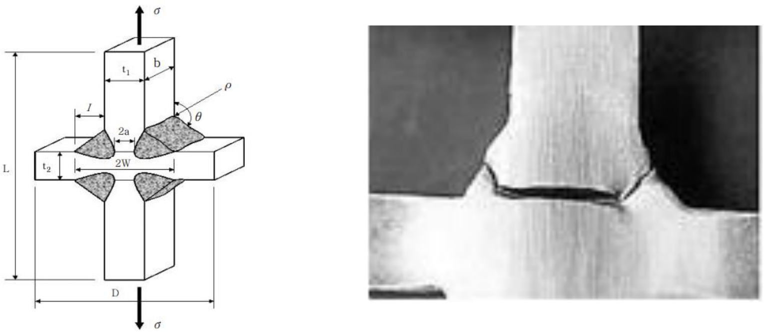
Table 1. *Terms and designations according to EN 1993-1-8, AWS A3.0, ISO 2553 and DIN EN ISO 17659*

Standard	Weld penetration (WP)		Depth of fusion (DOF)		Throat thickness (TT)	
	Definition	**Figures**	**Definition**	**Figures**	**Definition**	**Figures**
EN 1993-1-8	Full penetration butt weld	(-) No Figure	(-) No Definition	(-) No Figure	TT of fillet weld	Figure 1 (a)
	Partial penetration butt weld	(-) No Figure			TT of deep penetration fillet weld	Figure 1 (b)
AWS A3.0	Root penetration	Figure 3 (a)	Depth of fusion	Figure4	Actual TT	For convex, Figure 5 (a)
	Joint penetration	Figure 3 (b)			Effective TT	For concave; Figure 5 (b)
ISO 2553	Penetration depth	For full penetration; Figure 6 (a)	(-) No Definition	(-) No Figure	Nominal TT	Figure 7 (a)
		For partial penetration, Figure 6 (b)			Deep penetration TT	Figure 7 (b)
DIN EN ISO 17659	Fusion penetration	Figure 8	(-) No Definition	(-) No Figure	Effective TT	Figure 9
					Actual TT	
					Design TT	
	Root penetration				Maximum TT	

There are many studies on the static and/or dynamic behavior of full and partial penetration welded joints and the influence of arc welding process parameters [11-16]. In fillet welds, WP, DOF or TT is the values that the designer will determine according to the load on the structure. Each welded joint is subjected to different types of loads depending on the condition of the structure, in which case these values must be determined by the designer. In many studies, to determine the WP, DOF or TT, specimens are subjected to weld cross section tests then these values are obtained from the cross section view (CSV). Some standards such as EN 1993-1-8 describe what the minimum values of anom and cnom in terms of POF as shown in Figure 2. In this standard, it is identified that the sum of the lengths of anom1 and anom2 must be greater than or equal to the material thickness and cnom should be smaller of t/5 and 3mm.

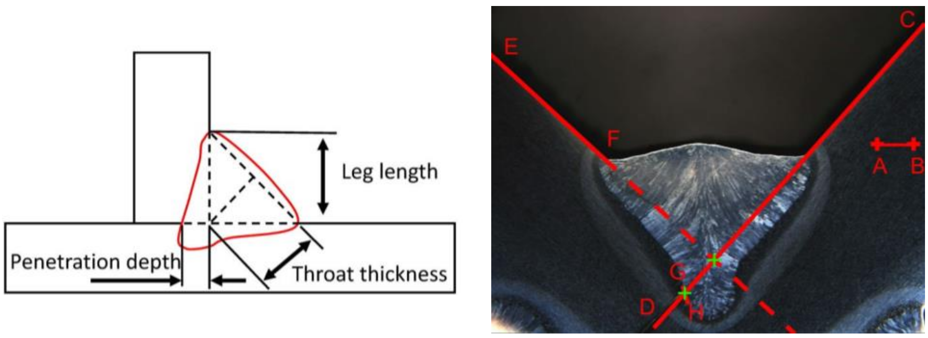
Wojsyk and Kudla [11] studied on the quantitative conditions and limitations of the use of butt, fillet and butt-fillet welds in modern welded constructions. In this study, EN 1993-1-8 standard was taken into consideration for demonstration and calculation of anom1, anom2 and cnom. Lee et al. [12] performed the fatigue tests on the cruciform fillet weld joints. The samples were manufactured with different cnom values as load carrying and non-load carrying. The samples were then evaluated in terms of fatigue strength. In this study, FOP condition of cruciform welded joints was evaluated according to EN 1993-1-8 standard.

Configuration and view of the load carrying specimen are shown in Figure 10. Mansour et al. [13] performed a probabilistic model of weld penetration depth based on process parameters. In this study, weld penetration depth was defined as distance the fusion line extends in the root between the web and flange plates. In addition measurement procedure of weld penetration depth was defined and depth was measured taking into consideration standard deviations as shown in Figure 11. Line GH as shown in Figure 11 was defined as weld penetration depth and then this value was measured. Chen et al. [14] carried out the experimental study on the performance of single welded joints. H shaped steel members were welded with different welding parameters to obtain the difference FOP values. In order to determine the FOP values, DOF was taken into consideration for each welded specimen. Moreover, DOF was defined in two ways as maximum penetration (Rm) and penetration in conjunction (Rj) separately. Rm and Rj are shown in Figure 12. In a study by Hanji et al. [15], weld leg length, the length of the unfused portion (2a), and the WP were measured and then incomplete penetration ratio (2a/tp) in the specimen was determined as in the Figure 13. In this study, Hanji et al. made an evaluation of penetration ratio according to EN 1993-1-8 standard. Unfused portion (2a) was measured from the point where the two fusion lines are closest to each other. Measurement results and ratio values of partial joint penetration (PJP70) specimen is given in Table 2. Sim et al. [16] studied on the effects of fabrication procedures on fatigue resistance of welded joints in steel orthotropic decks. To observe the effects of penetration, partial joint penetration (PJP) and %100 penetration welds were prepared and subjected to the fatigue tests. To determine the penetration ratio, specimens were cut into small pieces and subjected to the etching. The penetration rate was determined by the ratio of penetration depth to material thickness as in the Figure 14.



(a) (b)

Figure 10. *Configuration and view of the load carrying specimen; (a) Configuration of cruciform welded joints, (b) Cruciform specimen view [12]*



(a) (b)

Figure 11. *Illustration of weld bead geometry and CSV of welded specimen; (a) defined bead geometry, (b) CSV of welded specimen [13]*

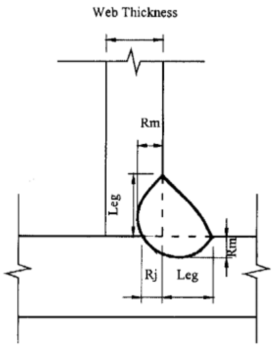
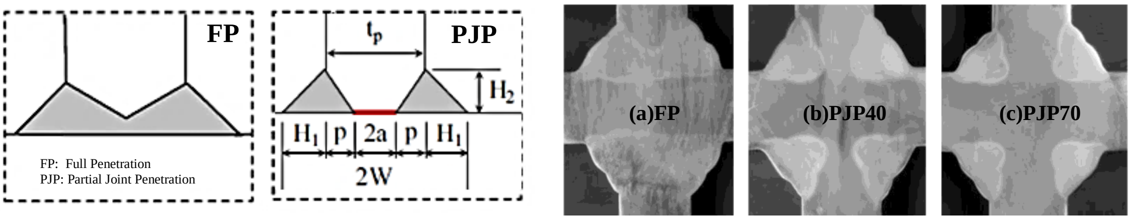


Figure 12. *Illustration of Rm and Rj for DOF [14]*

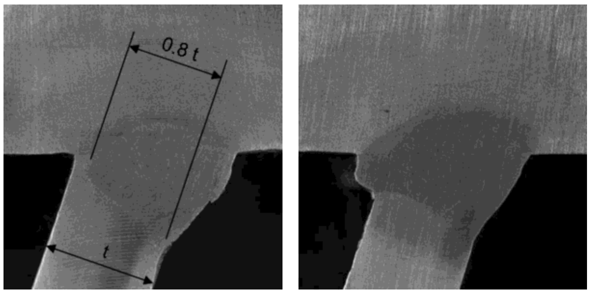


(a) (b)

Figure 13. *Illustration and CSV of welded specimens; (a) detail of welded part, (b) macrographs of specimens [15]*

Table 2. *Measurement results of PJP70 [15]*

Specimen name	t_p (mm)	2a (mm)	H_1 (mm)	H_2 (mm)	2W (mm)	P (mm)	$2a/t_p$	a/W	H_1/t_p
PJP70	22	16,02	10,53	11,15	43,07	2,99	0,73	0,37	0,48



(a) (b)

Figure 14. *CSV of welded specimens; (a) %80 PJP weld, (b) % 100 penetration weld [16]*

Different methods are also being developed to obtain WP, DOF or TT. Weld pool surface depth measurement studies have been carried out using a calibrated camera and structured light. Saeed et al. [17] presented a technique to obtain the surface information as penetration depth of the weld pool from the captured images by using a calibrated charge coupled device sensor and structured light. Similar to this method, simulation algorithms have also been developed to measure the depth of weld pool. In their study, to determine the 3D weld pool surface from specular reflection of laser beams, new computation method was presented. Apart from this method, non-contact ultrasound methods and Laser/EMAT ultrasonic techniques are used to determine the WP, DOF or TT [18-21]. Yang et al. [18] studied on the measurement of WP depths in thick structures based on ray-tracing of laser-generated bulk and surface waves by The Laser/EMAT ultrasonic (LEU) technique. To predict WP depths accurately, an artificial neural network is developed. Especially evaluation of WP depths on thick structures was performed by LEU technique.

As a result, WP, DOF and TT defining weld bead geometry is described by different definitions in related standards. WP is explained by different terms and definitions in these standards as root-joint penetration, penetration depth, full-partial penetration. Definition of DOF is only defined in AWS A3.0. TT is explained by three different definitions as actual, effective and theoretical throats in AWS A3.0, by two different definitions as nominal and deep penetration TT in ISO 2553, by two different definitions as TT of fillet weld and deep penetration fillet weld in EN 1993-1-8, by four different definitions as effective, actual, design and maximum TT in DIN EN ISO 17659. When looking at these terms and definitions, it is seen that terms defined by the standards do not correspond to each other in some cases and assessments are always made in terms of unit of length. Moreover, the evaluation of FOP rate on fillet welds is mostly performed as the ratio of the maximum FOP depth to the material thickness. Depth assessment (as unit of length) is often not ideal for accurate evaluation of FOP rates especially on fillet welds. Assessment taking into consideration unit of area will be more suitable as it allows accurate assessment of FOP rates in welded joints. On the CSV of the fillet welds, area of FOP can be determined and the FOP rate can be determined by proportioning this area to the total area (TA). In this case, a more accurate assessment can be performed to determine the FOP rates.

2. SUGGESTION FOR ASSESSMENT

The formation of the weld geometry depends on the torch angle and oscillation [22-24]. Besides the torch oscillation or angle, welding parameters also affect the dimensions of the weld geometry. Therefore, a uniform DOF may not always be obtained, especially in fillet welds having deep penetration in the weld root (as shown in Figure 15). For these reasons, while the maximum depth value (h1 is “max.” DOF and h1>h2) is obtained in a very small area, the depth may be low in other areas. Each side of the fillet welds should be assessed according to the area of FOP.

Calculation of area of FOP can be made by different methods such as numerical integration methods, multivariate image analysis [25-26]. Trapezoidal rule, Simpson's rule, or Hough transformation which are the numerical methods can be used to measure the irregular shape of the area of FOP. Multivariate image analysis is a method that has been used for the detection of uncertain areas in recent years [25]. Apart from the methods mentioned above, it is also possible to evaluate the weld CSV by transferring it to tracing paper. With these methods, the area of FOP in each side of fillet weld can also be determined. FOP rate is obtained by the ratio of the area of FOP to the TA, as shown in Figure 16. TA is obtained by multiplying thickness by the length which is between weld root and weld toe.

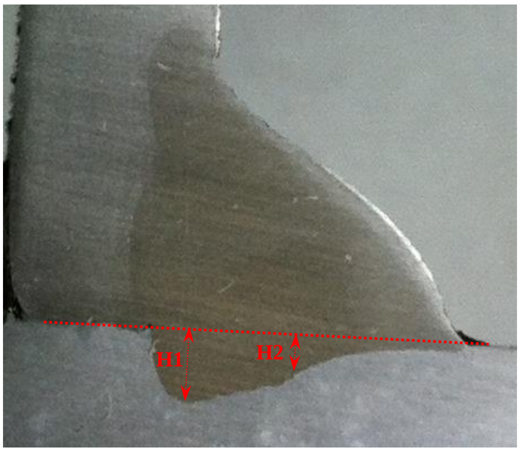


Figure 15. *DOF of welded specimen according to AWS A3.0*

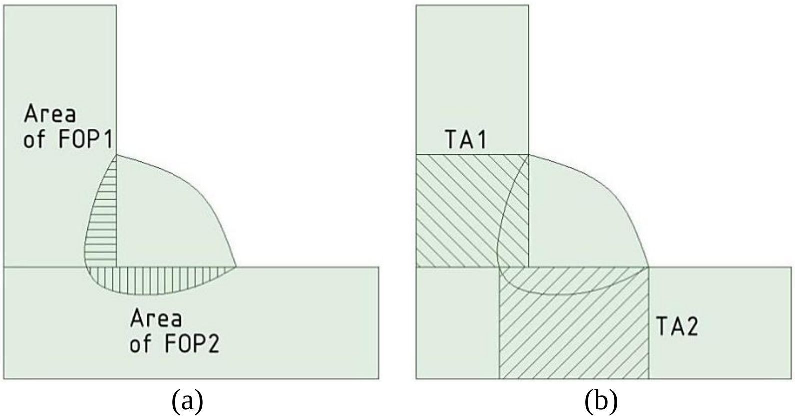


Figure 16. *Area of FOP and TA of each side; (a) area of FOP, (b) TA*

The study shown in Figure 17 carried to determine the effects of welding parameters on DOF of welded joints. After the welding process, welded specimens were cut into small pieces and subjected to the etching. Measurements were made on the CSV after etching. The measurement results are given in the Table 3 in terms of both unit of length and area. Although DOF of both samples is almost the same for weld A and weld B, the Area of FOP of the second specimen is larger than first specimen. Furthermore, the FOP rate calculated in terms of unit of area will always be lower than the unit of length. This case shows us that the evaluation of the FOP rate by considering unit of length is insufficient.

FOP rate is approximately fifteen percent taking into consideration unit of length for Weld A and Weld B. FOP rate taking into consideration unit of area is nine point seven percent and fourteen point seven percent for Weld A and Weld B, respectively.

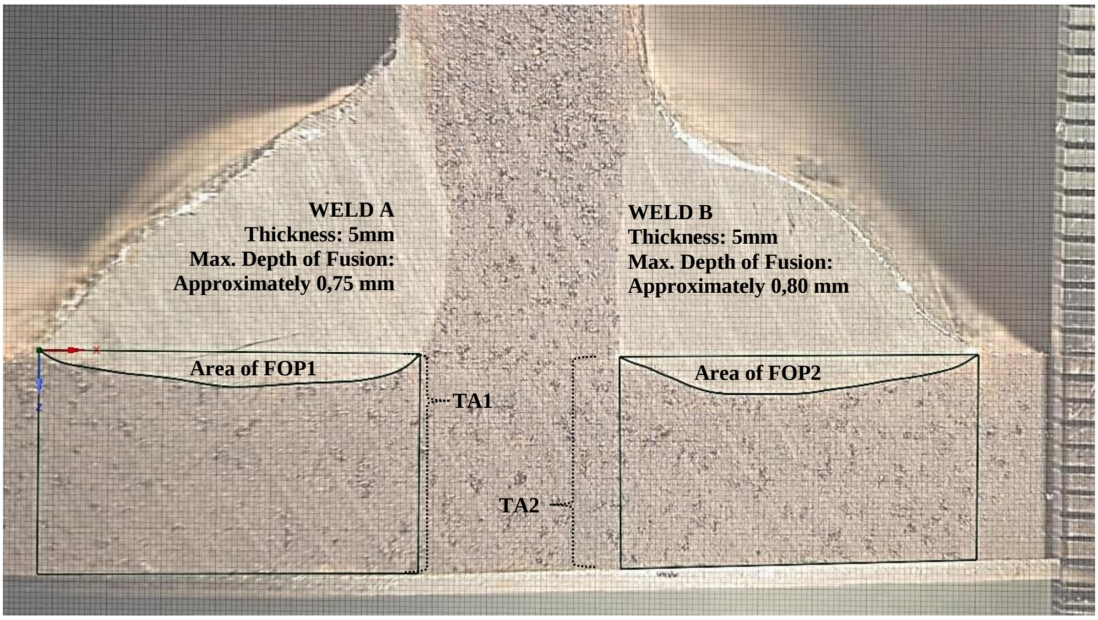


Figure 17. *CSV of welded specimen*

Table 3. *FOP rate in terms of unit of length and area*

Weld	FOP Rate (Depth of Fusion / Material Thickness)	FOP Rate (Area of FOP / TA)
Weld A	0,153	0,097
Weld B	0,162	0,147

There are many standards such as EN 1993-1-8, AWS A3.0, ISO 2553 and DIN EN ISO 17659 to describe the WP, DOF or TT. Each standard uses its own definitions for these terms and makes the necessary definitions for the weld geometry separately. All terms and definitions related to WP, DOF and TT are summarized in Table 1. Definitions in these standards are always made in terms of unit of length. Moreover, in many studies, the FOP rate is calculated in terms of unit of length instead of area. Method taking into consideration unit of area will be more suitable as it allows accurate assessment of FOP rates in welded joints. For welded specimen shown in Figure 17, FOP rate in terms of unit of length is close to each other for Weld A and Weld B. In terms of unit of area, FOP rate of Weld A and Weld B is nine point seven percent and fourteen point seven percent, respectively. As a result, evaluation in terms of unit of area instead of length gives more accurate results.

3. CONCLUSION

This paper presents the review of the standards defining WP, DOF and TT in fillet welds. For fillet welds, WP, DOF and TT are crucial dimensions to define the weld geometry. In this review, some standards such as EN 1993-1-8, AWS A3.0, ISO 2553 and DIN EN ISO 17659 are reviewed and then compared to each other. Each standard makes its own definition related to WP, DOF and TT. In these standards, it is seen that definitions are always made in terms of unit of length. In addition to these terms, the FOP rate is calculated in terms of unit of length in almost all studies. Assessment in terms of unit of length is not ideal for evaluation of FOP rate especially on fillet welds. It would be more appropriate to consider the unit of area, as it allows the FOP ratio to be evaluated more accurately in welded joints. Based on the assessments the following conclusions can be made;

- WP is defined by different terms and definitions in these standards as root-joint penetration, penetration depth, full-partial penetration.
- DOF is only defined in AWS A3.0.
- TT is explained by three different definitions as actual, effective and theoretical throats in AWS A3.0, by two different definitions as nominal and deep penetration TT in ISO 2553, by two different definitions as TT of fillet weld and deep penetration fillet weld in EN 1993-1-1, by four different definitions as effective, actual, design and maximum TT in DIN EN ISO 17659.
- Terms defined by these standards are often not the same and assessments for terms are always made in terms of unit of length.
- Assessments taking into consideration unit of area are more suitable as it allows accurate assessment of FOP rates in welded joints.

As a result of this review, it is concluded that it may not be correct to make a FOP rate evaluation considering unit of length. It will be more accurate to evaluate the FOP value and its rate in terms of area instead of the length.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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