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The Effects of Undercut Depth and Length on Weldment Mechanical Properties

Memduh KURTULMUŞ[1*]

[1]Marmara University, Faculty of Applied Sciences, Department of Jewelery and Jewelery Design, İstanbul, Türkiye

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Abstract

Undercutting is a fusion welding defect that appears as a groove at the weld metal's toe. An undercut discontinuity forms when welding, particularly when the current is applied at an extremely rapid rate. It decreases the static and fatigue strength of the weld and produces stress concentration at the welding zone. The height of the reinforcement, the weld bead's contact angle, the undercut's breadth, depth, length, and root radius, as well as other factors, affect the stress concentration factor's size. In this study, two mild steel plates with a 20 mm thickness were welded together using gas metal arc welding. Each test plate was machined to have a 30° single bevel groove angle prior to welding. The butt welded plate underwent radiographic NDT testing. A weldment free of defect was created. The weldment was machined into typical test specimens for tensile strength. An undercut defect was simulated by drilling a groove through each tensile test sample. Grooves had different depths and lengths. After that, samples were put through a tensile test. The test findings allowed for the identification of the impacts of groove shape on tensile strength, ductility, and static stress concentration factor.

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Author ID (ORCID Number)

0000-0001-6525-232X Memduh KURTULMUŞ

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1. INTRODUCTION

In connecting the workpieces of a construction, a welding technology is commonly used. Butt welding joints are commonly used in welding operations. Welding discontinuities occur at the weld zone if optimum welding parameters are not used in the welding operation (Hou et al., 2020). An undercut is a common discontinuity which appears at the toe of the butt weld bead (Ottersböck et al., 2021). An undercut is a type of weld defect presents in a fusion weld process (Frostevarg & Kaplan 2014; Meng et al., 2017; Hu et al., 2018). These discontinuities, which look like grooves and notches, appear parallel to the weld bead. They locate on the boundary between the weld zone and the base metal. Figure 1 depicts the undercut defect formed in X-butt weld joints created using the submerged arc welding technique (Zong et al., 2016). There are generally two different undercut defects: Discontinuous and continuous undercuts. Discontinuous defects involve a change in the defect thickness along the weld bead. The inability of weld areas to be filled with liquid weld metal during solidification causes undercuts. The undercut defect develops while welding with an extraordinarily high welding current or welding at an abnormally high welding speed. (Zong et al., 2016).

When a structural component's shape is uneven and the flow of stress is interrupted, stress concentrations result. A geometric discontinuity which causes a localized increase in stress is called as a stress raiser (Juvinall & Marshek, 1991). Holes, grooves, notches, and changes in the cross-sectional area of the object are stress raisers. The elasticity theory and the measurements acquired using the photo-elasticity technique are used to determine the maximum stresses in the notches and discontinuities of the objects under a static load. The stress that will exist in defect free piece is named as the nominal stress. The degree of concentration of a discontinuity

*Corresponding Author, e-mail: memduhk@marmara.edu.tr

under tensile loads can be expressed as a non-dimensional stress concentration factor K_t which is the ratio of the highest stress occurring at the toe of a stress raiser to the nominal stress (Juvinall & Marshek, 1991).

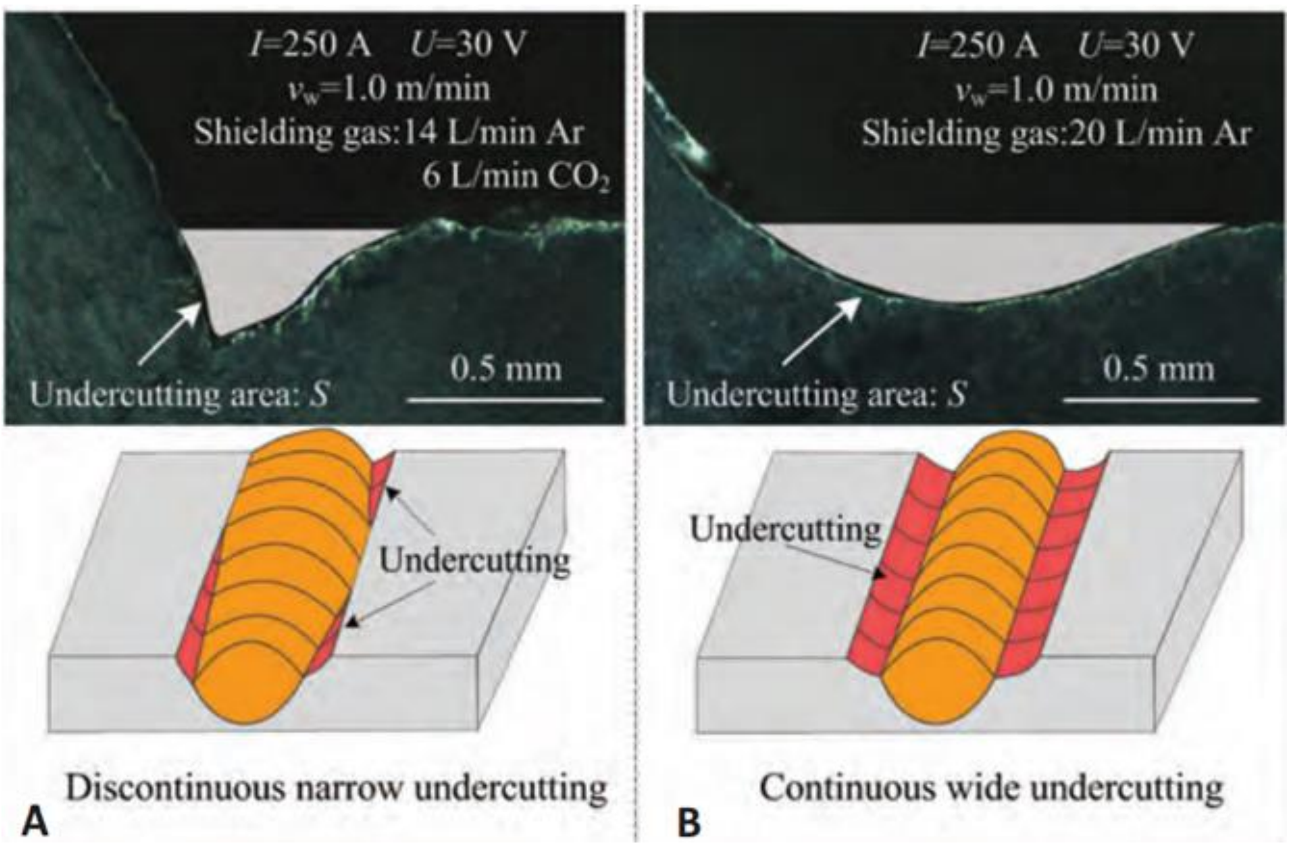

Figure 1. *Two different undercut discontinuities formed in butt weld joints made with gas metal arc welding* ***A)*** *Discontinuous narrow undercutting defect* ***B)*** *Continuous wide undercutting (Zong et al., 2016)*

The stress is concentrated at the bottom of an undercut because it has a notch-like effect (Juvinall & Marshek 1991) In butt welded joints, stress concentration occurs at the undercut which initiates a crack when the weldment is subjected to dynamic loads (Liinalampi et al., 2019; Molski & Tarasiuk, 2020; Kurtulmuş & Doğan, 2021; Kiraz et al., 2023). Fatigue cracks always start at stress raisers easily (Liinalampi et al., 2019). The K_t stress concentration coefficient in butt welds varies with the width, bottom radius, depth of the undercut and the weld contact angle (Cerit et al., 2010). Gill and his friends found that the stress concentration coefficient was dependent on the plate thickness, reinforcement height, weld bead width, and the weld bead contact angle (Gill & Singh, 2012). The effects of undercut length on the concentration of static stress were examined in a different study (Kurtulmuş & Doğan, 2021). An undercut defect causes a significant decrease both in the static strength (Kurtulmuş & Doğan, 2021) and the fatigue life of the structure (Liinalampi et al., 2019).

The effects of depth and length of continuous undercut defects on tensile strength, stress concentration coefficient (K_t) and ductility of weldments were experimentally investigated in this study. The mechanical properties of weldments were adversely affected with the undercut depths and lengths.

2. MATERIAL AND METHOD

In the experiments, two pieces of 1000x300x20 mm dimensioned EN 10025 S235JR (1.0037) unalloyed steel plates were used. On the longitudinal side of the plates a 30^o bevel angel was machined. Angular distortion of the weldment was prevented by a reverse bending of the plates before the welding operations. Butt welding was done with an automatic CO_2 shielded gas metal arc (MAG) welding machine. In operations EN ISO 14341-A G3Si1 welding wires were used. Following each welding procedure, a penetrating liquid test was done. The produced weldment was radiographically examined to ensure that it was defect free.

Tensile test pieces perpendicular to the welding direction were cut from the weldment. The specimens were prepared according to ASTM standards (ASTM, 2015). The welding zone of each specimen was polished with sandpapers. The details of the weld zone became apparent by macro etching the specimens with nital solution. The contact angle of the weld bead was measured as 164°.

A notch resembling the undercut defect was formed at the base metal boundary parallel to the weld bead with a wire erosion device. A continuous notch was drilled on one side of the specimen. The tensile test specimens are shown in Figure 2. Each notch contained 1 mm width and 0.5 mm root radius. Three specimens having the same notch were prepared. The details of the notches are given at the Table 1. In the specimens the notch depth was 1, 2 or 3 mm and the notch length varied between 5, 10 and 20 mm. There are three tensile specimens for the welded state as well as the notched condition. The specimens of the sample group 1 didn't contain a notch.

Figure 2. *Photographs of tensile test specimens*

Table 1. *Details of the undercut grooves*

Sample No	Undercut depth, mm	Undercut length, mm
1	0	0
2	1	5
3	1	10
4	1	20
5	2	5
6	2	10
7	2	20
8	3	5
9	3	10
10	3	20

Tensile testing was conducted using a 50 tons capacity electronically controlled hydraulic test machine. The ultimate tensile strength and elongation percentage values were determined. Thirty experiments were conducted because there were three comparable test samples in ten separate experimental groups. By computing the simple average of three test results with a similar notch, the characteristics of each sample group were ascertained. By dividing the ultimate tensile strength of the notch-free first sample by the ultimate tensile strength of the sample group, the static stress concentration coefficient of each sample group was computed.

3. RESULTS AND DISCUSSION

The Table 2 displays the tensile test results and the computed static stress coefficient (K_t) values of samples. The following graphs were drawn by using the results of the Table 2.

Table 2. *The tensile test results, elongation % and the calculated static strength coefficient,* K_t

Sample No	Ultimate tensile strength MPa	Elongation %	Calculated Kt coefficient
1	551	30.1	1.00
2	507	28.4	1.08
3	501	24.3	1.10
4	492	17.9	1.12
5	498	19.2	1.11
6	487	16.5	1.13
7	466	9.8	1.18
8	497	18.2	1.11
9	464	14.3	1.19
10	422	8.0	1.31

Figure 3 shows the link between the length of the undercut with different undercut depths and the ultimate tensile strength of the weldment. In sample 2 the notch size is the smallest. The undercut length was 5 mm, and the notch depth was only 1 mm. Even this smallest notch caused a fall of the tensile strength from 551 MPa (Sample 1) to 501 MPa. The strength decreased 8%. The ultimate tensile strength of the weldment decreased to 492 MPa when the notch length increased from 5 mm to 20 mm. The strength decreases slightly with the undercut length. Figure 3 shows that the fall ratio in tensile strength with the undercut length is getting bigger with the notch depth. The strength decrease ratio was 8% for 5 mm long undercut, 9% for 10 mm length and 10% for 20 mm undercut length. The Table 3 was prepared by the results of the Table 2 to reveal the notch geometry factor on the tensile strength ratio. The data in Table 3 clearly shows that the notch depth and length play a significant role in the static strength of welds. The ultimate tensile strength of the weldment is further decreased when an undercut is longer and deeper. The largest stress reduction was achieved with an undercut length of 20 mm.

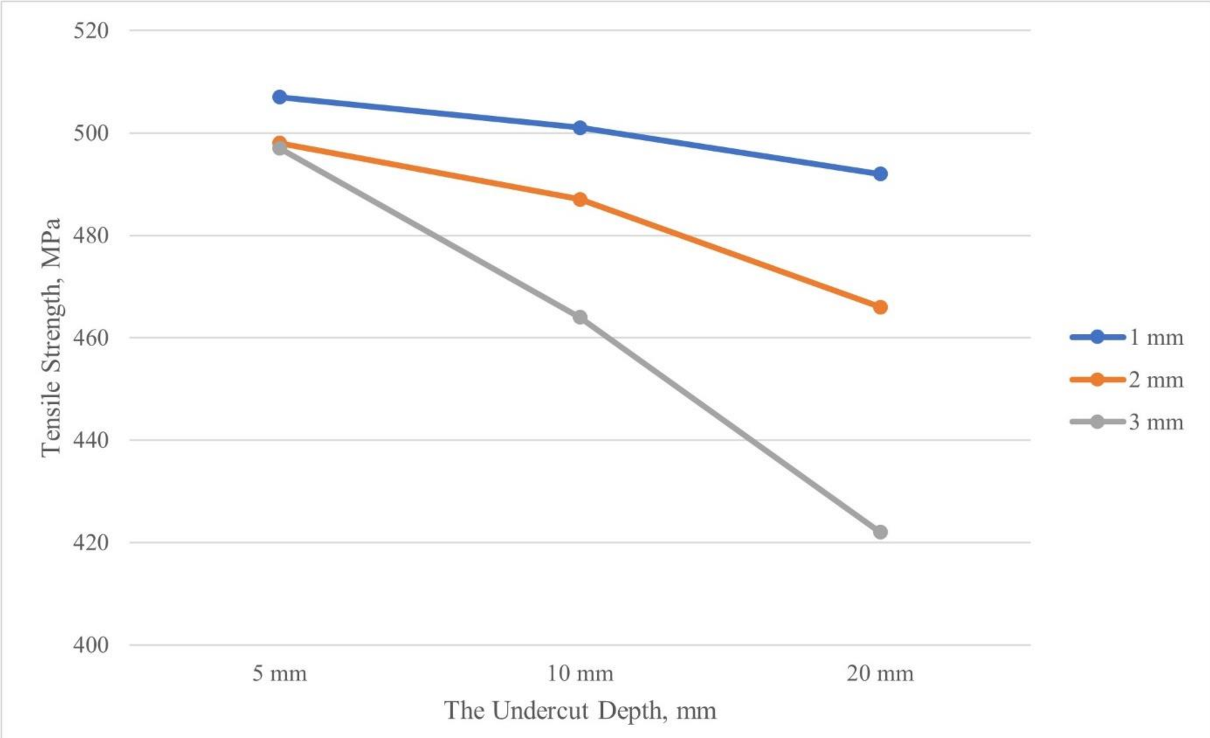

Figure 3. *Variation of the ultimate tensile strength with the length of the undercut*

Table 3. *Variation of the ultimate tensile strength loss percentage with the undercut length and the undercut depth*

	***Undercut* length, mm**		
Undercut depth, mm	**5**	**10**	**20**
1	8%	9%	10%
2	10%	12%	15%
3	10%	16%	23%

Figure 4 shows how the length of the undercut affects the static stress coefficient (K_t) of the weld. The stress concentration coefficient was approximately equal for 5 mm undercut length of 1, 2 and 3 mm undercut depth. K_t increases in direct proportion to the length and depth of undercut because the ultimate tensile strength of notched welds decreases with increasing the notch size. The K_t increase was calculated for 20 mm undercut lengths. If Figures 3 and 4 are compared, it will be seen that the length and depth of the undercuts have a similar effect on the mechanical properties.

The relationship between the undercut length and the weldment's elongation ratio is seen in Figure 5. The size of the notch affects how ductile a weldment is. Figure 5 clearly differs from Figures 3 and 4 in several ways. When the undercut depth is increased from 1 mm to 2 mm in each notch length, a noticeable decrease in ductility is seen. However, there is a little loss in ductility when the undercut is deepened from 2 mm to 3 mm. The Table 4 was prepared by the results of the Table 2. This table shows how the notch geometry factor affects the weldments' ductility ratio. Examining the data reveals the impact of undercut depth on ductility loss in weldments with an undercut length of 5 mm. Weldment ductility is 6%, 36%, and 40% for undercut depths of 1, 2, and 3 mm, respectively. The ductility is reduced 6% for 1mm undercut depth. The reduction in elongation is 30% for increasing the notch depth from 1 mm to 2mm. The elongation fall is only 4% in increasing the depth from 2 mm to 3mm. Similar results were obtained in 10 mm and 20 mm undercut lengths.

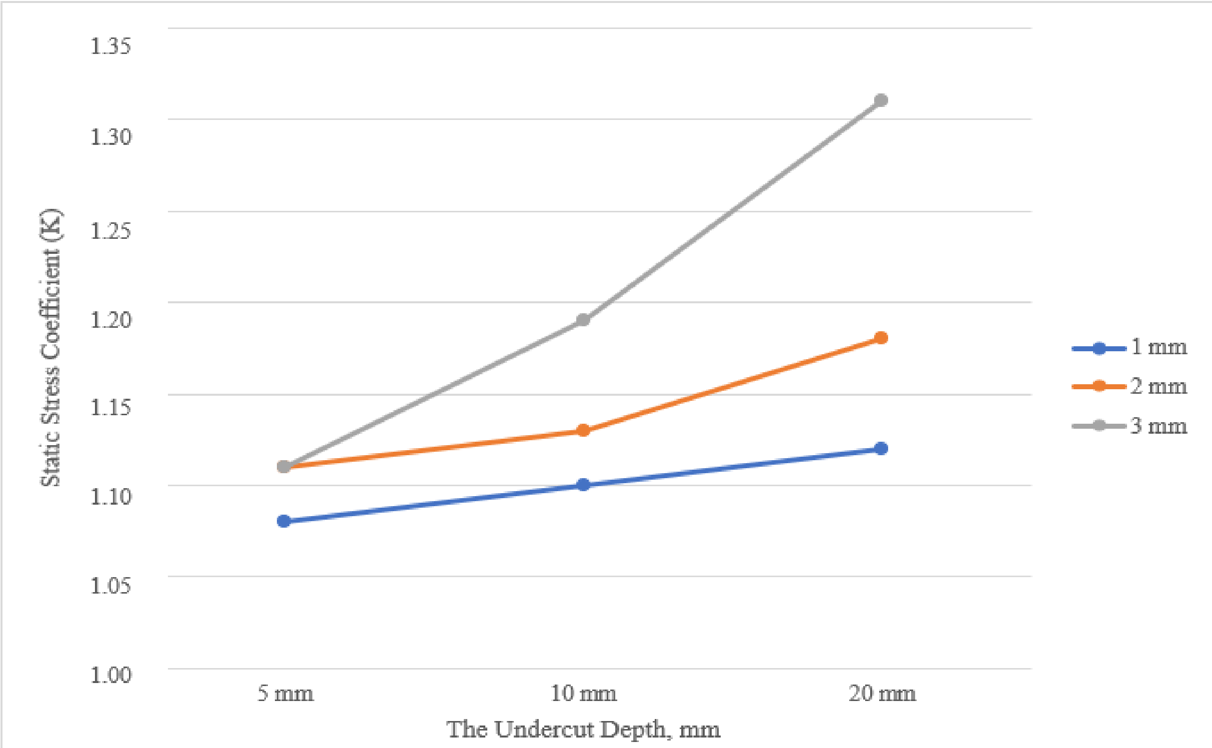

Figure 4. *Variation of the static stress concentration coefficient (K_t) with the undercut length*

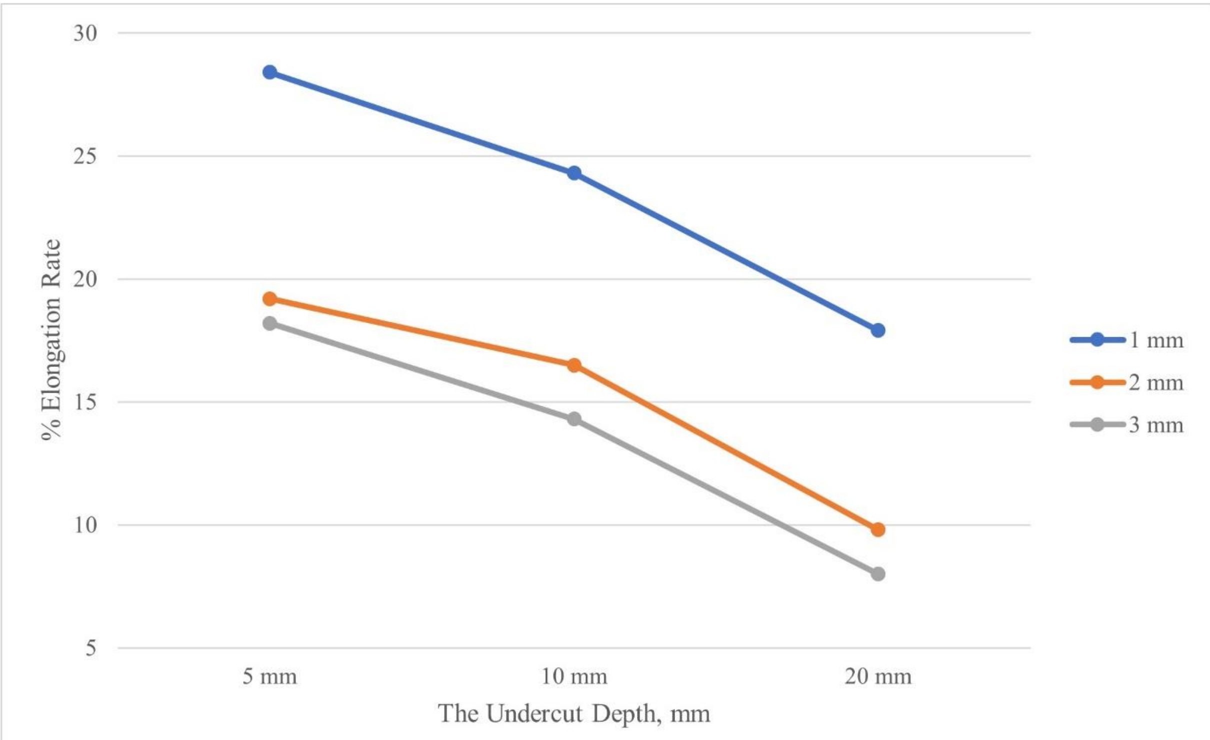

Figure 5. *Variation of weldment elongation % with the length of the undercut*

Table 4. *Variation of the elongation decrease percentage with the undercut length and the undercut depth*

	***Undercut* length, mm**		
Undercut depth, mm	**5**	**10**	**20**
1	6%	19%	41%
2	26%	45%	68%
3	40%	52%	73%

4. CONCLUSION

The 60° V-butt welded joint was made by the MAG gas arc welding process on 20 mm thickness EN 10025 S235JR (1.0037) unalloyed steel plates. The following results were obtained from the tensile tests:

1. The ultimate tensile strength decreases with the undercut depth increase.

2. The ultimate tensile strength decreases with the undercut length increase

3. The stress concentration coefficient of the discontinuity grows as the undercut's depth or length increases.

4. The ductility decreases with the increase of undercut depth and length.

5. The highest ductility loss is obtained when the undercut depth is 2 mm.

6. The findings of this study led to the realization that a more precise equation is required in the literature in order to anticipate and identify the static stress concentration factor of undercut defects in future studies and researchs.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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