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Comparison of electrode diameter-based and heat input-based methods for estimating the number of weld passes in Shielded Metal Arc Welding (SMAW)

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Abstract

Selecting the appropriate number of weld passes is an important step in Shielded Metal Arc Welding (SMAW) because it influences weld quality, heat input, productivity, and metallurgical characteristics of the welded joint. Existing approaches, such as the heat input-based procedure proposed by Trindade, provide reliable estimates by considering welding heat input and allowable thermal limits but require detailed welding parameters that are often unavailable during the initial stage of welding procedure planning or impractical to calculate on the production floor. This study proposes a simplified empirical equation for estimating the required number of SMAW weld passes using only plate thickness and the smallest electrode diameter. The proposed equation was evaluated by comparison with a modified heat input-based procedure derived from Trindade and integrated with EN 1011-2:2001 through Carbon Equivalent (CET) assessment. The comparison was conducted for single V-groove butt joints in the 1G position using a 2.6 mm E7016 electrode on plate thicknesses of 5, 8, 10, 12, and 16 mm. The proposed method predicted 2, 4, 4, 5, and 7 weld passes, whereas the modified heat input method required 2, 4, 6, 8, and 15 passes, respectively. Both methods produced identical results for plate thicknesses up to 8 mm; however, the discrepancy increased for thicker plates because the proposed equation does not account for groove geometry, welding travel speed, deposition rate, or heat input. The results demonstrate that the proposed equation provides a rapid and practical preliminary estimation tool for low-thickness SMAW joints, enabling fabrication personnel to estimate the required number of weld passes within seconds using only readily available parameters before detailed heat input verification is performed.

1. Introduction

Shielded Metal Arc Welding (SMAW) is one of the most widely used fusion welding processes in structural steel fabrication because of its versatility, portability, and relatively low equipment cost. For medium- and thick-section steel plates, multipass welding is generally required to achieve complete joint penetration while maintaining acceptable weld quality. The number of weld passes directly influences deposition efficiency, heat distribution, weld bead geometry, residual stresses, and the mechanical properties of the welded joint. Consequently, accurately estimating the required number of weld passes is an essential step in welding procedure planning [1], [2], [3], [4], [5], [6], [7], [8], [9].

Previous studies have shown that welding heat input significantly affects the thermal cycle experienced by the welded joint and therefore influences the size of the heat-affected zone (HAZ), microstructural evolution, residual stress, distortion, and susceptibility to hydrogen-assisted cold cracking. Based on these considerations, Trindade [10] proposed a heat input-based approach for estimating the required number of weld passes by comparing the calculated heat input with the maximum allowable value recommended by EN 1011-2 [11]. This method provides a rational basis for controlling thermal effects during multipass welding but requires detailed welding parameters, including welding current, voltage, travel speed, deposition rate, and process efficiency.

In practical SMAW fabrication, however, these welding parameters are often not available during the initial stage of welding procedure planning. Instead, fabrication engineers generally begin by selecting the plate thickness and electrode diameter before determining the remaining welding parameters. In addition, the selected welding current must remain within the manufacturer's recommended operating range for the chosen electrode diameter to ensure stable arc characteristics, adequate penetration, and acceptable weld quality. Consequently, a simple estimation method based on readily available fabrication parameters would be beneficial during the early planning stage [12].

Therefore, this study proposes an empirical equation for estimating the number of SMAW weld passes using only the plate thickness and the smallest electrode diameter. The proposed equation is intended as a rapid preliminary estimation method that can be applied before detailed welding parameters are established. Its performance is subsequently evaluated by comparing the estimated number of weld passes with those obtained using the heat input-based method proposed by Trindade [10]. Through this comparison, the study assesses whether the proposed equation can serve as a practical engineering tool for preliminary welding procedure planning while remaining consistent with established thermal design principles.

2. Research methods

This study compares two approaches for estimating the required number of weld passes in Shielded Metal Arc Welding (SMAW). The first approach is an empirical equation developed to estimate the number of weld passes from readily available fabrication parameters. The second approach follows the heat input method proposed by Trindade, which determines the required number of weld passes based on welding heat input and the thermal limitations specified in EN 1011-2. The agreement between the two methods was subsequently evaluated to determine the applicability of the proposed equation as a practical preliminary estimation tool. The overall research procedure is illustrated in Fig. 1.

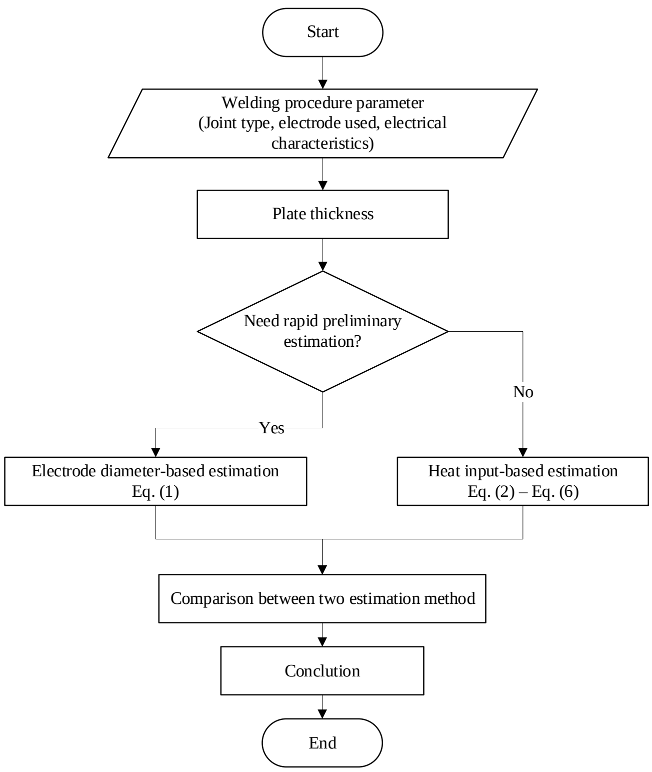

Fig. 1. Comparison of weld pass estimation methods.

2.1. Electrode diameter-based estimation

The proposed estimation method was developed empirically based on common SMAW fabrication practice, in which the smallest electrode diameter governs the amount of weld metal deposited during each welding pass. The method requires only two input parameters that are generally known before welding parameters are finalized: the plate thickness and the smallest electrode diameter selected for welding. The required number of weld passes is estimated using Eq (1).

$$np = \frac{tm}{de} + 1 \qquad (1)$$

where *np* is the required number of passes, *tm* is plate thickness (mm), and *de* is the smallest electrode diameter used (mm).

The additional constant (+1) was introduced empirically to represent the cap pass commonly deposited after the groove has been filled. The cap pass provides the final weld reinforcement and bead profile required in typical SMAW butt-joint fabrication. Since the calculated value may not be an integer, the estimated number of weld passes is rounded to the nearest whole number to ensure complete groove filling and adequate weld reinforcement.

2.2. Heat input-based estimation

The second estimation method is adapted from the heat input procedure proposed by Trindade and further integrated with the material assessment requirements specified in EN 1011-2:2001 [10], [11]. Unlike the proposed electrode diameter-based equation, this method estimates the required number of weld passes based on the thermal energy introduced during welding. In the present study, Trindade's procedure was modified by incorporating Carbon Equivalent (CET) evaluation prior to the heat input verification, allowing the allowable heat input to be selected according to the metallurgical characteristics of the base material.

Following Trindade's procedure, the deposited weld cross-sectional area was first determined from the groove geometry. An additional 10% of the groove area was included to account for the weld reinforcement, as assumed in Trindade's study. The total deposited weld area was therefore calculated using Eq. (2) [10].

$$A_d = 1.1\left(g t_r \frac{(t - t_r)^2 \tan(0.5 \times \theta)}{2}\right) \qquad (2)$$

where A_d is the deposited weld cross-sectional area including reinforcement (mm²), g is the root gap (mm), t is the plate thickness, t_r is the root face (mm), and θ is the groove angle (∘).

The welding travel speed was then estimated using the conservation of deposited weld metal calculated using Eq. (3) [10].

$$u = \frac{\dot{m}}{\rho A_d} \qquad (3)$$

where u is the welding travel speed (mm/min), $\dot{m}$is the filler metal deposition rate (kg/min), ρ is the density of the deposited weld metal (kg/mm³), and A_d is the deposited weld cross-sectional area (mm²).

The welding current was selected according to the manufacturer's recommended operating range for the selected SMAW electrode to ensure stable arc characteristics, adequate penetration, and acceptable weld quality. The corresponding welding voltage and travel speed were then selected in accordance with the applicable Welding Procedure Specification (WPS). The welding heat input was subsequently calculated using Eq. (4) [10].

$$Q = \frac{kVI}{u} \qquad (4)$$

where Q is the heat input (kJ/mm), k is the thermal efficiency of the SMAW process, V is the welding voltage (V), I is the welding current (A), and u is the welding travel speed (mm/s).

To determine the allowable heat input limitation, the Carbon Equivalent (CET) of the base material was calculated using Eq. (5) [11].

$$CET = C + \frac{Mn + Mo}{10} + \frac{Cr + Cu}{20} + \frac{Ni}{40} \quad (5)$$

where C, Mn, Mo, Cr, Cu, and Ni are elemental compositions in wt%.

The calculated CET value was used to determine the allowable heat input range according to EN 1011-2:2001, Method B. The standard recommends different heat input limitations depending on the hardenability of the steel, as represented by its CET value. In this study, ferritic steels with CET values of 0.20, 0.30, and 0.40 were evaluated using an allowable heat input range of 0.5 to 4.0 kJ/mm in accordance with the applicability conditions of EN 1011-2:2001.

The calculated heat input was then compared with the allowable maximum heat input, Q_{max} When the calculated heat input exceeded the permissible limit *($Q > Q_{max}$)* the required number of weld passes was determined using the pass ratio proposed by Trindade using Eq (6) [10].

$$N' = \frac{Q}{Q_{max}} \quad (6)$$

where *N'* is the pass ratio, *Q* is the calculated welding heat input, and Q_{max} is the maximum allowable heat input determined from the CET classification.

The final number of weld passes was obtained by rounding *N'* upward to the nearest whole number.

2.3. Comparison of estimation methods

The proposed electrode diameter-based estimation was compared with the modified heat input-based method to evaluate its applicability as a preliminary tool for SMAW welding procedure planning. The comparison was conducted for single V-groove butt joints in the flat (1G) welding position using plate thicknesses of 5, 8, 10, 12, and 16 mm.

A 2.6 mm E7016 electrode was selected for all welding cases. Based on the manufacturer's recommendation, the welding current was fixed at 75 A, while the welding voltage was maintained at 22 V. A thermal efficiency of 0.80 was adopted for the SMAW process. The filler metal deposition rate was assumed to be 0.8 g/min, and the density of deposited steel was taken as 7.85×10^{-6} kg/mm³. The groove geometry consisted of a single V-groove with a 60° included angle, 1.5 mm root gap, and 1.0 mm root face. Following Trindade's procedure, an additional 10% weld reinforcement was included in the deposited weld area calculation [10], [11].

For each plate thickness, the required number of weld passes was first estimated using the proposed electrode diameter-based equation (Eq. 1). The same joint configuration was subsequently analyzed using the modified heat input-based method. The deposited weld area, welding travel speed, welding heat input, pass ratio, and final number of weld passes were determined according to Eqs. (2) - (6). The estimated number of weld passes obtained from both methods was then compared to evaluate the capability of the proposed empirical equation to provide a practical preliminary estimation before detailed thermal verification [10], [11].

3. Result and discussion

This chapter presents the estimated number of weld passes obtained using the proposed electrode diameter-based method and the modified heat input-based method. The comparison was performed for single V-groove butt joints (Fig. 2) with plate thicknesses of 5, 8, 10, 12, and 16 mm using a 2.6 mm E7016 electrode in the 1G welding position. The welding parameters used for the heat input calculation were selected according to the manufacturer's recommendation, consisting of a welding current of 75 A and a welding voltage of 22 V. As shown in Fig. 2, the groove geometry consisted of a single V-groove butt joint with a 60° included angle, a 1.5 mm root gap, a 1.0 mm root face, and a plate thickness (t) that varied from 5 to 16 mm. A deposition rate of 0.8 g/min, deposited metal density of 8 $\times 10^{-6}$ kg/mm³, and SMAW thermal efficiency of 0.80 were assumed throughout the analysis. The allowable heat input was taken as 4.0 kJ/mm in accordance with EN 1011-2:2001 for ferritic steels.

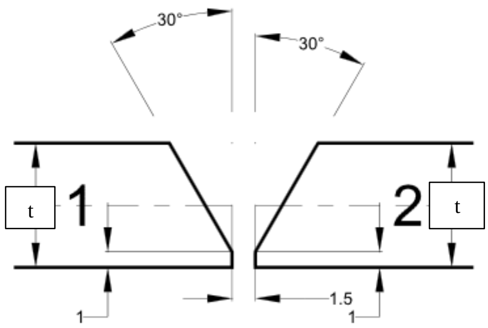

Fig. 2. Geometry of the single V-groove butt joint.

3.1. Electrode diameter-based estimation

The proposed empirical equation estimates the required number of weld passes solely from the plate thickness and the smallest electrode diameter. Since the electrode diameter remained constant at 2.6 mm, only the plate thickness influenced the estimated number of weld passes. The results are summarized in Table 1.

Table 1. Estimated weld passes using the proposed method

Plate thickness (mm)	Electrode diameter (mm)	Calculated np	Rounded np
5	2.6	2.92	2
8	2.6	4.08	4
10	2.6	4.85	4
12	2.6	5.62	5
16	2.6	7.15	7

The proposed equation predicts that the required number of weld passes increases almost linearly with plate thickness because the estimation depends only on the ratio between plate thickness and electrode diameter. No thermal or metallurgical considerations are included in this estimation.

3.1. Heat input-based estimation

The modified heat input method estimates the required number of weld passes based on groove geometry, deposition rate, welding travel speed, and calculated heat input. The allowable heat input was limited to 4.0 kJ/mm according to EN 1011-2:2001 [11].

Table 2. Estimated weld passes using the heat input method

Plate thickness (mm)	Groove area Ag (mm²)	Deposited area Ad (mm²)	Travel speed u (mm/s)	Heat input Q (kJ/mm)	Required passes N
5	7.12	7.83	0.217	6.09	2
8	16.65	18.31	0.093	14.23	4
10	25.88	28.47	0.06	22.13	6
12	37.43	41.17	0.041	32.00	8
16	67.45	74.20	0.023	57.66	15

The calculated heat input increased considerably with plate thickness because the larger groove cross-sectional area reduced the welding travel speed required to maintain the specified deposition rate. Consequently, the required number of weld passes increased to maintain the heat input below the allowable limit.

3.3. Comparison of estimation methods

The comparison between the proposed electrode diameter-based estimation and the modified heat input procedure is presented in Table 3. The proposed method estimates the required number of weld passes using only the plate thickness and electrode diameter, whereas the modified Trindade method considers groove geometry, deposition rate, welding travel speed, heat input, and the allowable thermal limits specified by EN 1011-2:2001 [11]. Consequently, the heat input method incorporates both geometric and metallurgical considerations, while the proposed equation is intended only for preliminary estimation during welding procedure planning.

Table 3. Number of weld passes between two methods.

Plate thickness (mm)	Electrode diameter method	Heat input method	Difference
5	2	2	0
8	4	4	0
10	4	6	2
12	5	8	3
16	7	15	8

For plate thicknesses of 5 mm and 8 mm, both methods produced identical estimates, as illustrated in Fig. 3. This agreement indicates that the proposed empirical equation is capable of providing a reliable preliminary estimate for relatively thin plates where the deposited weld volume and heat input remain relatively low. Under these conditions, plate thickness is the dominant parameter governing the required number of weld passes, making a simple geometric relationship sufficient for initial planning.

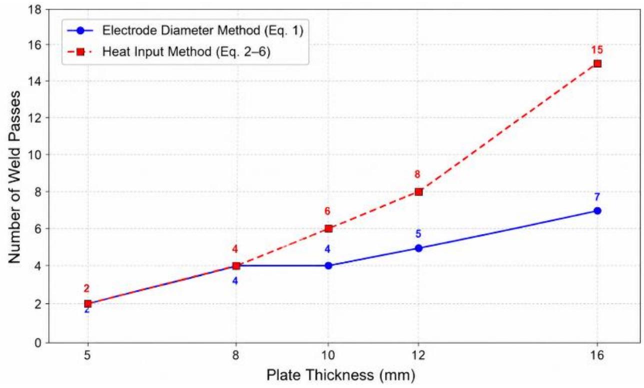

Fig. 3. Estimated weld passes by both methods.

For plate thicknesses of 10 mm and above, the difference between the two methods increases progressively. The proposed equation estimated four, five, and seven weld passes for 10, 12, and 16 mm plates, respectively, whereas the modified Trindade procedure required six, eight, and fifteen passes to maintain the allowable heat input below 4.0 kJ/mm. The increasing discrepancy results from the larger groove cross-sectional area associated with thicker plates, which reduces the welding travel speed for a constant deposition rate and consequently increases the calculated heat input. Because the proposed equation does not account for thermal energy, deposition rate, or welding travel speed, it progressively underestimates the number of weld passes as the plate thickness increases.

The comparison also highlights the complementary nature of both approaches. Trindade's [10], [11] procedure is intended to optimize welding parameters based on thermal considerations and is therefore more appropriate once the welding procedure specification has been established. However, the method requires several input parameters, including groove geometry, deposition rate, welding current, voltage, travel speed, process efficiency, and allowable heat input. These parameters are often unavailable during the initial planning stage. In contrast, the proposed equation requires only the plate thickness and electrode diameter, allowing a rapid estimation before detailed welding parameters are defined. Therefore, the proposed equation should not be considered a replacement for Trindade's heat input method but rather as a practical preliminary estimation tool that can be followed by heat input verification using the modified Trindade procedure.

The results indicate that the proposed equation is suitable for preliminary estimation of SMAW weld passes for low-thickness steel plates ranging from approximately 5 to 8 mm. Within this thickness range, the method provides estimates comparable to those obtained using the modified heat input procedure while requiring only the plate thickness and electrode diameter. Consequently, the estimation can be performed rapidly without calculating groove geometry, deposition rate, welding travel speed, heat input, or Carbon Equivalent (CET), making the method well suited for preliminary welding procedure planning and quick decision-making on the production floor. For thicker plates, where thermal effects become increasingly significant, the heat input-based method should be used to determine the final number of weld passes in accordance with EN 1011-2:2001.

4. Conclusions.

This study proposed a simplified electrode diameter-based equation for estimating the number of weld passes in SMAW and compared its performance with a modified heat input-based method adapted from Trindade and EN 1011-2:2001. The proposed method produced comparable results for plate thicknesses of 5 to 8 mm, demonstrating its suitability for preliminary weld pass estimation in low-thickness steel plates. However, the discrepancy increased for plate thicknesses of 10 mm and above because the proposed equation does not account for heat input and other thermal factors. Therefore, the proposed method is recommended as a rapid and practical preliminary estimation tool that can be easily applied during welding procedure planning or directly on the production floor, while heat input verification remains necessary for thicker plates to ensure compliance with EN 1011-2:2001.

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