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OPTIMIZATION OF FILLER METALS CONSUMPTION IN THE PRODUCTION OF WELDED STEEL STRUCTURES

ABSTRACT

The paper presents the some aspects of the optimization of filler metals consumption in the production of welded steel structures. Correct choice of beveling method can allow to decrease cost of production and increase quality. The review of calculation methods of filler metal consumption at the design stage was carried out. Moreover, the practical examples of amount of filler metals calculation were presented and analyzed. The article also contain examples of mobile apps which are makes it easy to see welding costs in just a few seconds. Apps as well as simple excel spreadsheets with correct mathematic equations allows to optimize welding process.

Keywords: *filler metal, optimization, steel structures, beveling, welding app*

INTRODUCTION

In the production of steel structures, it is possible to make both separable and inseparable joints. Among the second type, the most common are: butt, fillet and lap welds. Manufacturing, depending on the thickness of the wall may require preparation of the edges (beveling), usually by means of machining. Arrangement of two edges creates groove. During welding, groove is fulfilled by melted filler metal. Upon welding suitable quantity of heat should be introduced in order to melt filler metal and edges of groove, subsequently crystallization and cooling of weld were observed.

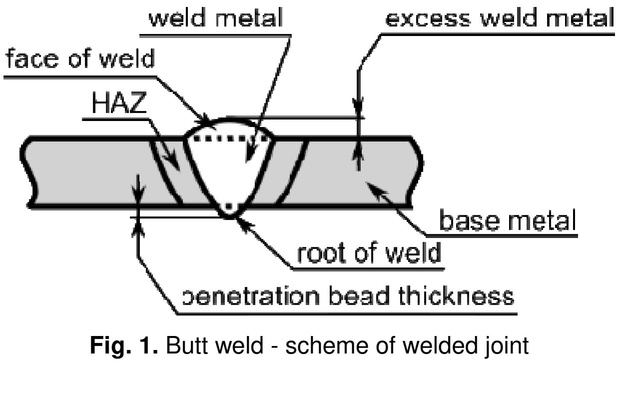


Fig. 1. Butt weld - scheme of welded joint

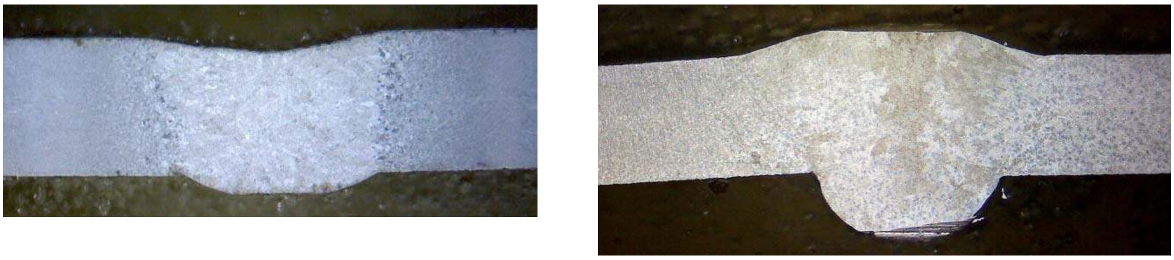


Fig. 2. Butt weld; a) non-alloyed steel, b) stainless steel

Introduced temperature gradient can cause microstructural transformation which corresponds with change of mechanical properties. Above mentioned factors contribute to the chemical inhomogeneities and forming three characteristic area: weld metal, heat affected zone (HAZ) and base metal (Fig.1). Optimization of filler metals consumption in fabrication of steel structures takes place due to costs of production and required mechanical properties of welds [1-5]. The examples of structural steel and austenitic stainless steel weld joints are presented in the Fig. 2a, 2b.

OPTIMIZATION OF CONSUMPTION

Filler metals consumption depending on the geometry of groove can be calculated in accordance with equations. Requirements connected with beveling were included in standards PN-EN ISO 9692 [5]. In Table 1 examples of beveling with proper equations to determine cross-section area, are shown. Estimation of weld length and metal density gives information about weight of weld which is connected with filler metal consumption. The cross-section area of joint shall also included area of penetration bead thickness and excessive weld metal that refer to the below equation.

$$F_{sp}=F_r+F_n+F_g \tag{1}$$

where:
F_{sp} – cross-section area of weld (mm^2),
F_r – cross-section area of groove (mm^2),
F_n – cross-section of excessive weld metal (mm^2),
F_g– area of penetration bead thickness (mm^2).

To obtain information about cross-section area of excessive weld metal and root face, equations (2) and (3) [2, 3] are given by:

$$F_n=\frac{2}{3}\cdot\Delta s_n\cdot W_n \tag{2}$$

$$F_g=\frac{2}{3}\cdot\Delta s_g\cdot W_g \tag{3}$$

where:
Δs_n Δs_g – height of excess weld metal and penetration bead thickness (mm),
W_n W_g – width of excess weld metal and penetration bead thickness (mm^2),
F_n – area of excess weld metal (mm^2),
F_g – area of penetration bead thickness (mm^2).

Table 1. *Selected means of beveling and equations to calculate width of groove (W_r) and cross section area of weld (F_r)*

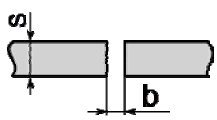
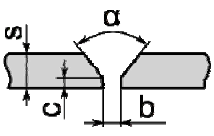
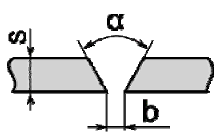
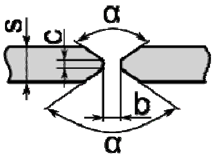
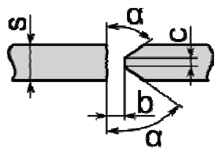
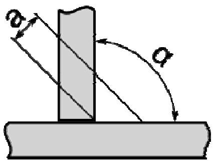
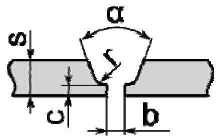
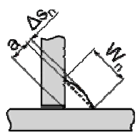
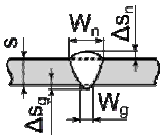
Joint edge preparation	Width of groove W_r and cross-section area of weld F_r	Joint edge preparation	Width of groove W_r and cross-section area of weld F_r
	$W_r = b$ $F_r = sb$		$W_r = 2(s-c)tg\frac{\alpha}{2} + b$ $F_r = sb + (s-c)^2 tg\frac{\alpha}{2}$
	$W_r = 2stg\frac{\alpha}{2} + b$ $F_r = s\left(b + stg\frac{\alpha}{2}\right)$		$W_r = (s-c)tg\frac{\alpha}{2} + b$ $F_r = sb + \frac{(s-c)^2}{2} tg\frac{\alpha}{2}$
	$W_r = tg\alpha\left(\frac{s-c}{2}\right) + b$ $F_r = tg\alpha\left(\frac{s-c}{2}\right)^2 + sb$		$W_r = 2tg\frac{\alpha}{2}a$ $F_r = a^2 tg\frac{\alpha}{2}$
	$W_r = 2tg\frac{\alpha}{2}[s-(r+c)] + 2r + b$ $F_r = \frac{\pi r^2}{4} + sb + \left\{2r + [s-(r+c)]tg\frac{\alpha}{2}\right\}[s-(r+c)]$		
b – gap; α – angle; s – thickness of base metal; c – depth of root face; r – radius; a – throat thickness			

Table 2. *Geometry requirements for excess weld metal and excess penetration. Quality level for fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) in accordance with BS ISO 5817*

Joint design	Thicknes s s, mm	Quality level D (low)	Quality level C (medium)	Quality level B (high)
	≥ 0.5	$\Delta s_n \leq 1$ mm+0.25W_n $\Delta s_n \leq 5$ mm	$\Delta s_n \leq 1$ mm+0.15W_n $\Delta s_n \leq 1$ mm+0.2a $\Delta s_n \leq 4$ mm	$\Delta s_n \leq 1$ mm+0.1W_n $\Delta s_n \leq 1$ mm+0.15a $\Delta s_n \leq 3$ mm
	≥ 0.5	$\Delta s_n \leq 1$ mm+0.25W_n $\Delta s_n \leq 10$ mm	$\Delta s_n \leq 1$ mm+0.15W_n $\Delta s_n \leq 7$ mm	$\Delta s_n \leq 1$ mm+0.1W_n $\Delta s_n \leq 5$ mm
	0.5÷3	$\Delta s_g \leq 1$ mm+0.6W_g	$\Delta s_g \leq 1$ mm+0.3W_g	$\Delta s_g \leq 1$ mm+0.1W_g
	≥ 3	$\Delta s_g \leq 1$ mm+1W_g $\Delta s_g \leq 5$ mm	$\Delta s_g \leq 1$ mm+0.6W_g $\Delta s_g \leq 4$ mm	$\Delta s_g \leq 1$ mm+0.2W_g $\Delta s_g \leq 3$ mm

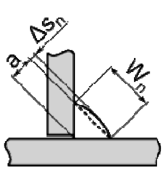
Depending on the welding method and design of joint, for butt weld width of excessive W_n is equal to the width of groove W_r plus 2÷4 mm [2, 3]. Width of root W_g is equal to the gap for single sided welds and second excess weld metal for double sided butt welds. Heights of excess weld metal (Δs_n) and penetration bead thickness (Δs_g) are related to widths W_n and W_g and should be every time related with established in advance quality level of weld. Example requirements for welds (steel, nickel, titanium and their alloys except for electron beam welded joints) are included in Table 2. Size of excess weld metal does not change strength and shall be reduced in accordance with the requirements of project in order to reduce manufacturing costs [1-4].

Calculation of filler metal consumption shall also include the material losses. Depending on the applied welding technology, some parts of filler can evaporated eg. MMAW or created spatter eg. MMAW and GMAW. Modern modification of traditional welding technologies providing controlled transfer of droplets from the wire to the weld pool, limiting spatter and thus material losses. Each of the filler metals are also characterized by a deposition efficiency ie. relationship of weld metal deposited to the weight of the electrode. In the case of gas welding or gas tungsten arc welding deposition efficiency is 100%, whereas for the gas metal arc welding or submerged arc welding values 97% to 100% are observed. The widest range of efficiency can be observed during welding with covered electrodes. Thin-coated electrodes without ferro-alloys in covering achieve only 60% due to burn off. On the other hand electrodes with high quantity of alloying element in covering reached even 160% [1-4]. Main features of welding method have influence on the unused electrode stub that is discarded, which generates losses. Electrode stub of covered electrode is 35÷45 mm, however stub of wire that is used in gas tungsten arc welding and gas welding is about 150 mm. Gas metal arc welding and submerged arc welding are methods in which a continuous and consumable wire electrode is fed through a torch but if the process will be stopped, welder or welding operator should cut off approximately 30 mm of wire before the next strike of arc.

Example 1

Designer proposed in the draft 50 mm of single side T-joint with fillet weld thickness a=3 mm. Welder for "increase protection" made a weld thickness of 4 mm with correct excessive weld metal that is fulfill the requirements of quality level B in accordance with PN-EN ISO 5817 [6]. Density of weld metal is ρ=7,85 g/cm^3 (theoretical value). Excessive convexity assumed as a maximum allowable for quality level B. Results of calculation were shown in Table 3.

Table 3. *Results of calculation for 1st example*

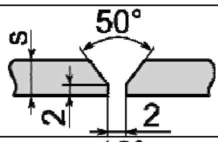
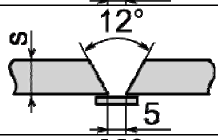
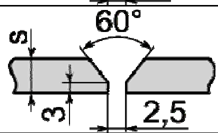
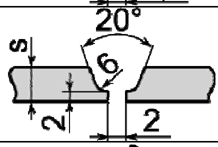
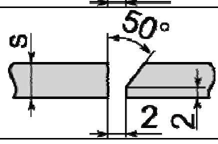
Design	Thickness a, mm	Area of groove F_r, mm^2	Weld width W_n, mm	Weld excess height ΔS_n, mm	Area of excess weld metal F_n, mm^2	Area of weld F_{sp}, mm^2	Filler metal consumption Z_s, kg/m
	3	9	6	1,6	6,4	15,4	0,121
	4	16	8	1,8	9,6	25,6	0,201

If the joint will be made properly weld metal consumption will be at 6.04 kg, As a result of the 4 mm thickness of the weld, additive material consumption has increased almost twice (10.05 kg).

Example 2

Single side butt welds of different thickness are performed using by gas metal arc welding. In order to optimize filler metal consumption, the most popular manners of beveling included in PN-EN ISO 9692-1 were analyzed [5]. Heights of excessive weld metal were chosen as the maximum for quality level B according to PN-EN ISO 5817 [6]. Density of weld metal ρ=7.85 g/cm^3. Calculations were carried out on 1 m weld and results are presented in Table 4.

Table 4. *Results of calculation for 2nd example*

Welding position according to ISO 9692-1	Type of beveling	Filler metal consumption Z_s kg/1 m of weld								
	Thickness of base metal, mm	4	6	8	10	12	14	16	18	20
1.3		**0.15**	**0.25**	**0.39**	**0.55**	0.75	0.98	1.25	1.55	1.86
1.4		0.26	0.36	0.47	0.58	**0.70**	**0.83**	**0.97**	**1.11**	**1.26**
1.5		0.16	0.26	0.41	0.60	0.83	1.11	1.42	1.75	2.11
1.8			0.37	0.60	0.84	1.10	1.36	1.64	1.92	2.21
1.9.2		0.16	0.28	0.45	0.66	0.91	1.20	1.52	1.87	2.26

Optimal consumption of filler metal for different thickness has been marked using the frames and shaded. Additional shaded cells represents the range of thickness suggested by PN-EN ISO 9692-1 for the type of bevel [5]. It is clearly shown that welding of 12 and 14 mm thickness elements is most cost-effective with beveling according to item 1.4, although the standard does not indicate this solution as optimal. An important limitation of this type of beveling is the necessity to use weld metal backing system that supports the molten metal. There are two ways, the first employs temporary backing eg. non-fusible copper backing which is removed after the weld is completed and the second backing becomes a part of weld. These solutions must be taken into account in the draft.

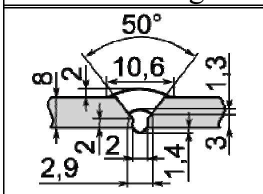
Example 3

The draft assumed 40 m of 8 mm butt weld that will be made using by MMAW. Groove was prepared in accordance with PN-EN ISO 9692-1 item 1.3 [5]. For welding the first layer electrodes 2 mm diameter and 300 mm length are recommended, but for the fill passes electrodes 4 mm diameter and 450 mm length. Efficiency of both covered electrodes is estimated at 80%. Required quality level B according to PN-EN ISO 5817 [6]. Welding with coated electrodes is connected with filler metal losses due to stubs estimated as 40 mm. Correct welding technology should ensured depth of fusion not less than 3 mm and minimizing excessive spatter up to 2% of weight of fulfilled layers. Spatter can cause many problems in manufacturing process, the most common except for losses of material are excessive clean-up and spatter balls sticking to tools. Density of weld metal is ρ=7.85 g/cm^3. Calculation results are included in Table 5.

Table 5. *Calculation results for third example*

Thickness s, mm	8	
	3	5
Area of groove F_r, mm^2	6.466	23.792
Weld width W_n, mm	2.933	10.596
Weld excess height ΔS_n, mm	1.293	2.06
Area of excessive weld metal F_n, mm^2	2.528	14.548
Penetration bead thickness ΔS_g, mm	1.4	0
Area of bead thickness F_g, mm^2	1.867	0
Area of butt weld F_{sp}, mm^2	10.861	38.341
Filler metal consumption Z_s, kg/m	0.085	0.301

Electrode size X, mm	Diameter x Length	
	2x300	4x450
Volume of electrode V_1, mm^3	942.478	5654.867
Weight of electrode m_1, g	7.398	44.391
Volume of weld metal V_2, mm^3	653.451	4039.334
Weight of weld metal m_2, g	5.13	31.709

	Type of pass	Number of electrodes L (general calculations)		Number of electrodes L (accurate calculations)	
		rods/m	rods/40 m	rods/m	rods/40 m
	Root pass	17	680	16.622	665
	Fill pass	10	400	9.492	380

Assumed conditions and general calculations provided information that will be necessary to use 17 electrodes 2 mm diameter and 10 electrodes 4 mm diameter in order to made 1 meter of weld and so 680 and 400 respectively to carried out 40 m of butt weld. Accurate calculations given quite different results 665 and 380 electrodes thus less 15 thin and 20 thick.

Welding programs

The calculations of filler metal consumption can be significantly improved by using even office software. One way is to prepare several excel spreadsheets for each type of beveling and equip them with the appropriate formulas and functions. Example of such excel spreadsheet is shown in Fig. 3.

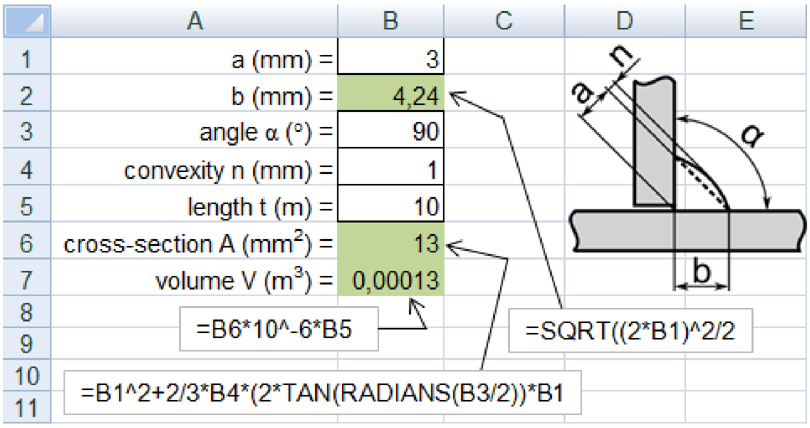


Fig. 3. Calculations performed in excel spreadsheet

Supporting software is often made by filler metal manufacturers for their clients. An example is „Welding Calculator" from Voestalpine [7], which is accessible through the website or application "Weld Wizard" from Fronius [8] also available for mobile devices with Android and iOS operating systems (Fig. 4).

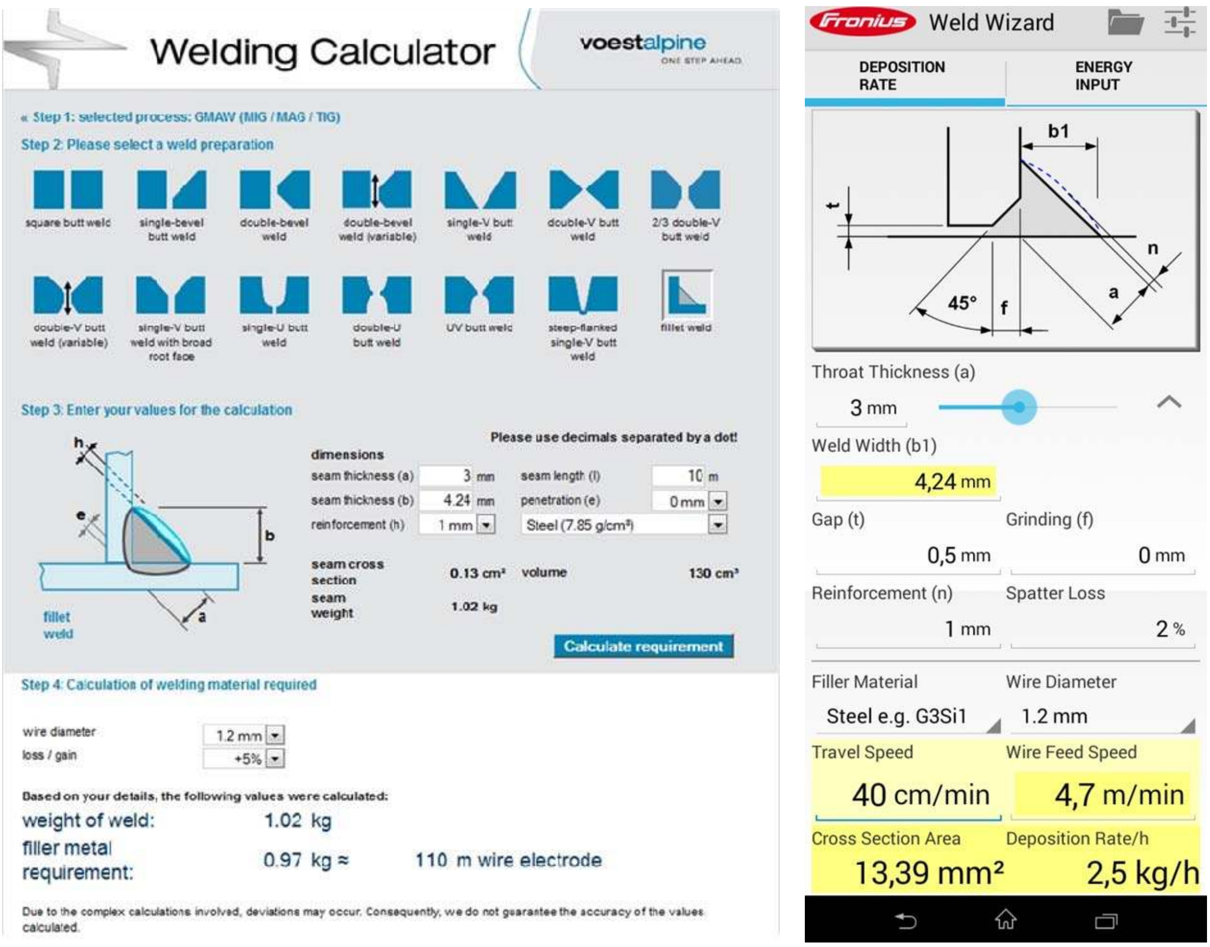


Fig. 4. Calculations performed in "Welding Calculator" and "Weld Wizard"

SUMMARY

Estimation of filler metal consumption is directly connected with subsequent consumption and cost as well as labor costs and materials (tools) used to bevel the edges. The optimal shape of weld groove can cause that the cost of making joint can be reduced by half or more. Implementation of above mentioned apps may contribute to increase the competitiveness of contractors, together with high quality and mechanical properties of welded joints.

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BIBLIOGRAPHY

1. Ferenc K. (Ed.), Welding Technology in Practice (in Polish), Verlag Dashofer.
2. Pilarczyk J. (Ed.) Engineer Guide. Welding (in Polish). Vol. 1, Wydawnictwa Naukowo-Techniczne, Warszawa, 2003.
3. Słania J., Welding Plans. Theory and Practice (in Polish), Agenda Wydawnicza SIMP, Redakcja Przeglądu Spawalnictwa, Warszawa, 2013
4. Ferenc K., Ferenc J., Welded Structures. Joints (in Polish), Wydawnictwa Naukowo-Techniczne, Warszawa, 2006
5. PN-EN ISO 9692-1: Welding and allied processes — Recommendations for joint preparation — Part 1: Manual metal-arc welding, gas-shielded metal-arc welding, gas welding, TIG welding and beam welding of steels
6. PN-EN ISO 5817: Welding -- Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) -- Quality levels for imperfections
7. http://boehler-welding-service.com/voestalpine/calculator/eng/ (07.06.15).
8. http://www.fronius.com/cps/rde/xchg/SID-0824496D-CF141849/fronius_international /hs.xsl/79_34740_ENG_HTML.htm#.VXRXElIXhVc (07.06.15)