Influence of Heat Input and Welding Position on Geometrical Properties of GMAW Fillet Welds of Unalloyed Steel

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Abstract **- This paper presents principal influences of heat input and welding position on geometrical properties of fillet welds for conventional and pulsed GMAW of unalloyed steel. We took into consideration geometrical properties such as fillet weld size, penetration, dilution and reinforcement. All presented influences are represented by fitting curves, based on simple linear regression of experimental data provided by visual and macro-section examination.**

Keywords **- GMAW, fillet weld, dimension.**

1. Introduction

In order to provide sufficiently sized (or designed) fillet welds in everyday production by use of any arc welding process, it is important to select proper set of essential welding parameters. Design size of fillet weld may be presented by its leg size (z, mm) or throat thickness (a, mm) (Fig. 1a). On the other hand, most influential welding parameters are welding current (I, A), arc voltage (U, V) and welding speed (w, cm/min). These three define important welding parameter, heat input (Q, kJ/mm), defined by Eq. 1.1.

$$Q = \frac{UI}{w}\eta \qquad 1.1$$

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Here, η denotes heat input efficiency, which generally can be taken as η=0.8 for conventional GMAW (Gas Metal Arc Welding). Fig. 1b shows basic geometrical properties of fillet weld. They can be measured in combination with visual examination and additional macro-section evaluation.

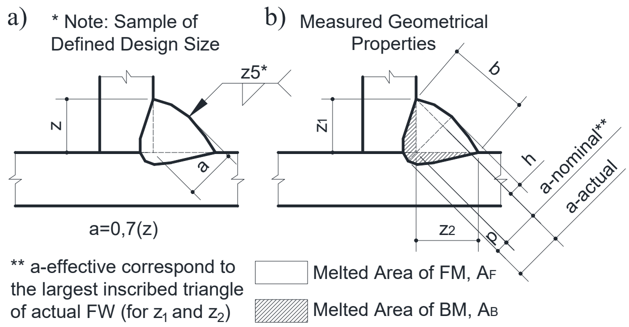


Figure 1. Geometrical properties of Fillet Welds

In accordance with standardized approach, geometrical properties of fillet weld should be determined with consideration of largest inscribed isosceles triangle (Fig. 1b). Thus, on single prepared fillet weld macro-section we can measure:

- area of melted Base Metal (A_B),
- area of melted Filler Metal (A_F),
- nominal throat thickness (a),
- "vertical" leg size (z_1),
- "horizontal" leg size (z_2),
- penetration (p),
- reinforcement (h), and
- face width (b).

Furthermore, dilution (D, %), which is another important geometry parameter of fillet weld, can be calculated as:

$$D = \frac{A_B}{A_B + A_F} \qquad 1.2$$

Obviously, D and p indicate involvement of base metal in effective size of fillet weld. If we consider only the visual testing of fillet weld, defined within respective Welded Product Standard, effective throat

(a), leg sizes (z_1 and z_2), reinforcement (h) and face width (b) they become the subject to inspection, regarding required fillet weld quality level.

In addition, only prepared macro-section of fillet weld can be used to measure A_B, A_F and p and to calculate dilution D afterwards.

Primary goal of fillet weld inspection and evaluation is comparison of throat size (nominal a_n or actual a_e, as depicted in Fig. 1b) or leg size (z, z_1 or z_2) with required (designed) size. Achieved nominal size cannot be smaller than designed, while minor larger sizes may be tolerated. Therefore, important question regarding technology arises: Which essential welding parameters should be chosen to achieve required design size and geometry of one fillet weld?

2. Literature Research

Terms and definitions of geometrical properties of fillet weld are well defined within ISO TR 25901-1 [1], while weld joint's imperfection tolerances for required quality levels are defined, in general, within ISO 5817 [2]. Principally, achieved fillet weld size (either a or z) has to be at least equal or higher than designed one, while minor increase in size is tolerated. Reinforcement h is tolerated within some limits regarding the size of fillet weld. For example, if weld size required by design is z5, maximum tolerated reinforcement for achieved fillet weld is h_{max}=1,7 mm for the highest quality level "B" [2]. Penetration p is always required, but there are no specific limits for its value. In general, increase of p is desirable and recommended.

Dilution D for welding of similar base metals is rather quantitative parameter, while for heterogeneous welding (dissimilar base metals) always presents important quality parameter. Dilution presents proportion of base metal within final microstructure of weld metal.

Obviously, abovementioned geometry parameters define strength and quality of produced fillet weld, made of base metals jointly with filler metal. Once created by selected welding procedure, all welds, including fillet welds, have to be the subject of visual inspection. Visual inspection is minimal requirement, but other non-destructive testing may be required as well, depending on general requirements of applicable welded product standard.

There are numerous researches regarding prediction and modelling of geometrical parameters, both of which for general type welds and for fillet welds only. They are all based on analysis of influence of welding parameters (I, U and w) on geometrical properties. Welding parameters are commonly represented through heat input Q, which is calculated as in Eq. 1.1.

Specifically, R. A Ribiero et al. (2015) had investigated influence of U and I on geometry (p, h, b and D), and developed rather complex model based on multivariate regressive curvilinear analysis [3].

M. Y. Yaakub et al. (2013) had investigated prediction of welding parameters on FW bead geometry in overhead (EN ISO mark "PD", AWS mark "4F") welding position. Research concluded with power function analysis of influence of heat input on geometry parameters (a, z, p and b) [4].

D. Sugitani and M. Mochizuki (2013) performed study of influence of geometrical properties (a and p) of fillet weld on static strength. They clearly concluded that penetration p is quite influential parameter, by mean the greater the p, the higher is strength of the weld joint. In addition, they clearly show high influence of heat input Q and welding position of achieved fillet weld size a on strength [5].

E. M. M. Belinga (2012) did research regarding influence of high heat input during pulsed GMAW welding on geometrical properties of fillet weld (z, a, p and h) . He had not provided any regression models, but had shown strong influence of Q on geometry, in general [6].

A. Kumar and T. DebRoy (2005) had investigated influence of welding parameters (U, I and w) on achieved weld geometry (a, z and p) by the use of genetic algorithm. Interestingly, they concluded their study with point that a given (designed or required) weld size can be obtained using various sets of welding parameters, in which the most influential parameter is welding current I [7].

E. J. Lima II et al. (2005) had used quite complex quadratic model for prediction of weld bead geometry (p, h, b and size of heat-affected zone, HAZ) based on input welding parameters (I, U, w and recorded weld pool width L). They used rather sophisticated approach by the mean of recording weld pool with high-speed camera (for acquisition of L) [8].

The most engineering-friendly model regarding prediction of fillet weld size z is provided by D. K. Miller and R. S. Funderburk (2001) [9], expressed as:

$$z = 5.5\sqrt{Q} \qquad 2.1$$

Here z is in millimetres and Q heat input in kJ/mm. In case z is defined, heat input Q is calculated as:

$$Q = \frac{z^2}{30.3} \qquad 2.2$$

Obviously, essential welding parameters (U, I, w), jointly represented through heat input Q, are the most influential on fillet weld geometry and its size. Therefore, the simple model by D. K. Miller and R.S.

Funderburk [9], as per Eq. 2.1, is used as a starting point for further study and evaluation.

3. Experiment

A series of fillet welds was made by using two variants of GMAW: the usual one (GMAW) and pulsed (GMAW-P). To evaluate influence of welding position [5] on weld geometry, two extreme welding positions were considered: flat (PB) and overhead (PD). Essential welding parameters were chosen to represent relatively limited heat input range. Limitation is set by the mean of manual welding (Tab. 1).

Table 1. Range of welding parameters

Welding parameters range		Heat input, Q (kJ/mm) GMAW	Heat input, Q (kJ/mm) GMAW-P
Welding current, I (A)	200-300 @ PB 160-260 @ PD	0.81-1.25 @ PB 0.65-1.46 @ PD	0.39-0.78 @ PB 0.43-1.39 @ PD
Arc voltage, U (V)	21-26 @ PB 20-25 @ PD		
Welding speed, v (mm/s)	3.6-7.2 @ PB 3.5-4.9 @ PD		

Heat input for GMAW-P was calculated according to general recommendation, and it is based on arithmetic mean power [10] for known welding wave current pattern from the used power source (Daihen Welbee WB-P500L). Calculation is the same as shown in Eq. 1.1 but using averaged (mean) values of current and arc voltage instead of peak ones.

The invariable welding parameters were:

- base metal: unalloyed steel S235JR – EN 10025-2 with 6 mm thickness,
- filler metal: solid wire G 42 4 M21 3Si1 – EN ISO 14341-A,1,2 mm diameter,
- shielding gas: 100 % CO_2 for regular GMAW and 82 % Ar+18 % CO_2 for GMAW-P, with flow of 15-17 l/min,
- filler metal - wire extension (equivalent to CTWD – Contact Tip to Workplace Distance): 12-15 mm.

After welding, all welded samples were visually examined, with direct measurement of z_1, z_2 and a_a (actual a). Based on this, achieved quality level is determined for the purpose of the further study (graded from "B" to "D" as per ISO 5817). In particular, reinforcement h was measured, due to the high values achieved in overhead position. Furthermore, middle sections of the fillet welds were cut, polished and etched for macro-section examination as per ISO 17639.

Using prepared macro-section samples, a number of geometrical parameters of fillet welds were measured and calculated: nominal throat thickness a_n, penetration p, reinforcement h and dilution D (based on A_B and A_F as shown in Fig. 1), as well as leg sizes (z_1 and z_2) and effective throat thickness a_e (as consequence of fillet weld asymmetry, e.g. variable and unequal z_1 and z_2).

All measurements were made indirectly using photos of macro-sections in AutoCAD, in scale 1:1.

Selected samples of examined macro-sections are shown in Fig. 2 and 3, where white lines are inscribed deliberately to express precisely FW cross-section geometry.

4. Results and Discussion

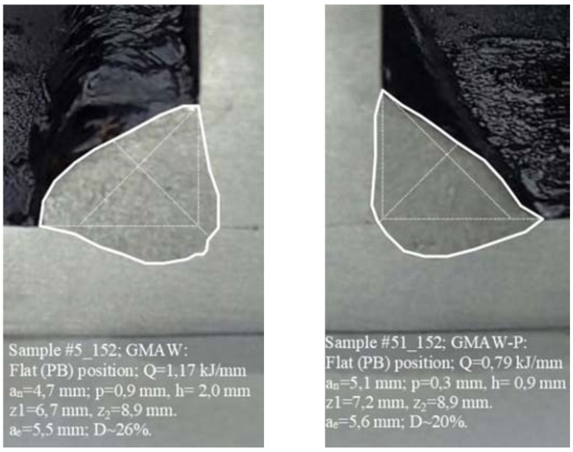
General conclusion from visual examination and macro-section evaluation show that pulsed GMAW requires lower heat input for the same size of fillet weld in comparison to regular GMAW. Compared with GMAW, minor spatter was observed on pulsed GMAW welded fillet welds, while face contour was more uniform. In addition, it is possible to conclude that higher reinforcement is always present in overhead (PD) welded fillet joints. This is obviously consequence of gravity effect on the weld pool.

Typical samples of macro-sections within examined fillet welds are shown in Fig. 2 and Fig. 3. Respective information regarding used heat input, welding position (PB or PD) and measured geometrical parameters are given. Thick solid lines represent the contour of melted metal (i.e. weld metal), while thin doted lines represent edges of base metals, largest inscribed isosceles triangle, and throat thickness line, respectively.

All measured geometrical parameters were further evaluated and analysed by the mean of simple linear regression analysis, according to the model of D. K. Miller and R. S. Funderburk and described with Eq. 2.1 (denoted as "est. AWS"). As this model is directly related to prediction of leg size z for known heat input Q, similar model is assumed for other geometrical parameters. This is possible because they have strong mutual correlation. In addition, fillet weld size represented as throat thickness a is used (generally used approach in Europe) instead of leg size z (generally used approach in USA).

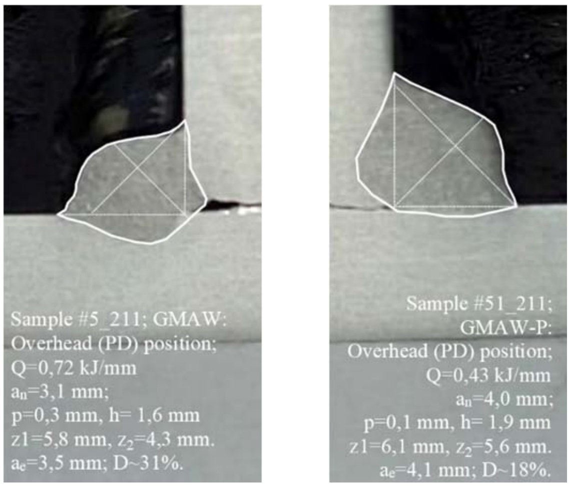
Thus, Fig. 4 shows dependence of effective throat thickness a_e on used heat input Q, both for regular and pulsed GMAW, irrespective of welding position. Provided regression equations prove conclusion that pulsed GMAW requires less heat input Q for the same size of fillet weld in comparison to regular GMAW. This also means that pulsed GMAW provides increased fillet weld sizes for the same value of heat input. Both welding processes provide close to or bit higher sizes (up to 40 %) of fillet weld in comparison to model established by D. K. Miller and R.S. Funderburk and described with Eq. 2.1.

Fig. 5 and Fig. 6 show dependence of penetration, p, reinforcement h and dilution D on used heat input Q. It should be mentioned that the general range of penetration is p_{min}/p_{max}=0,1/0,8 mm (with peak at 2,2 mm), for reinforcement h_{min}/h_{max}=1,3/4,0 mm and for dilution D_{min}/D_{max}= 6/41 %.



a) GMAW *b) pulsed GMAW*

Figure 2. Samples of fillet welds made in flat (PB) welding position



a) GMAW *b) pulsed GMAW*

Figure 3. Sample of fillet welds made in overhead (PD) welding position

The main difference between welds shown in Fig. 5 and Fig. 6 is the welding position. As it is possible to see, these are two extreme positions regarding gravity effect. On the subject of the general range of the penetration p (0,1-0,8 mm, with neglecting single extreme of 2,2 mm), it can be concluded that a bit higher p can be achieved in overhead position which is beneficial to the final strength of a fillet weld. Also, overhead position provides in average 54 % higher reinforcement in comparison to flat welding position. However, this could be detrimental to overall fillet weld quality. In the case of homogenous base metal welding, dilution D can contribute to the final strength of the fillet weld, in a similar manner as penetration p. Therefore, higher values of D are more desirable, and they are achieved in overhead welding position (approximately 40 % higher in comparison to flat).

Obviously, the heat input and welding position strongly influence the final geometry of fillet welds made by Gas Metal Arc Welding (GMAW).

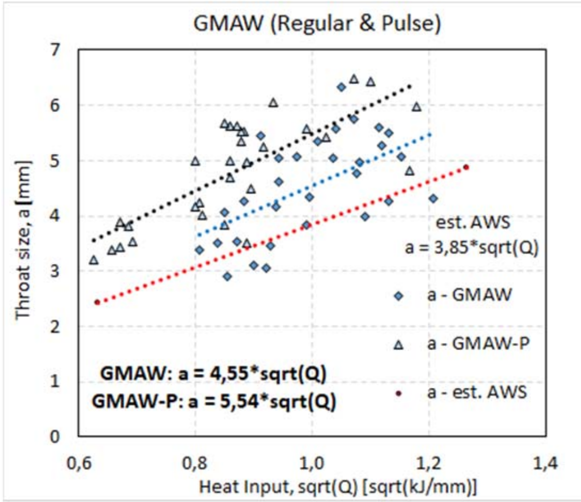


Figure 4. Throat size of fillet weld vs. heat input for GMAW and pulsed GMAW

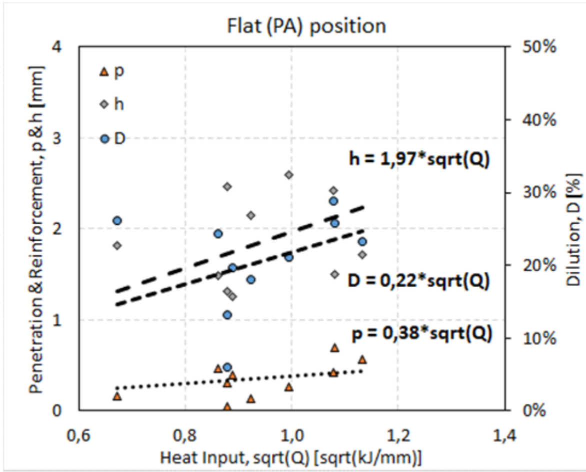


Figure 5. Penetration, reinforcement and dilution vs. heat input for flat position

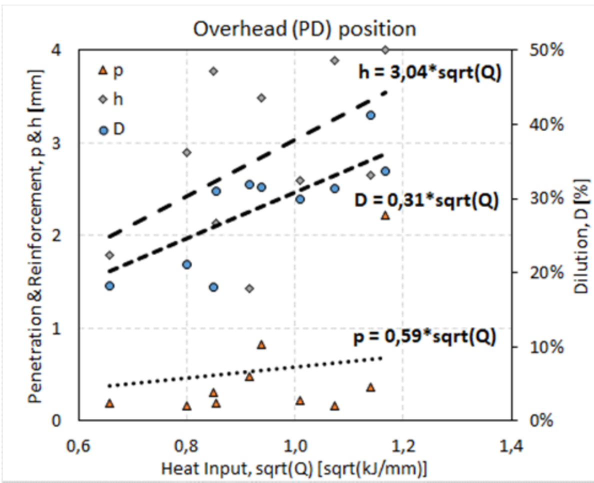


Figure 6. Penetration, reinforcement and dilution vs. heat input for overhead (PD) position

5. Conclusion

To achieve required (or designed) fillet weld size, it is of outmost importance to select appropriate essential welding parameters (i.e. welding current, arc voltage and welding speed), and they can be expressed through heat input. Heat input has the strongest influence on fillet weld geometry, which furthermore determines its effective strength and quality. The latter is always the subject of examination and evaluation by non-destructive testing in accordance with requirements of applicable welded product standards, codes or specifications.

This paper shows that linear model for prediction of fillet weld size based on known heat input, provided by AWS (D. K. Miller and R. S. Funderburk, 2001), shows quite conservative estimates in the case of GMAW (both regular and pulse). For the welding parameters presented in this paper, up to 40 % higher values for fillet weld throat thickness may be achieved. In addition, welding position may also strongly influence the achieved geometrical properties, namely penetration, reinforcement and dilution. All of them contribute to the final effective strength and quality of fillet weld. While the increased penetration and dilution are beneficial, the increased reinforcement may deteriorate weld quality. Therefore, it is possible to conclude that in overhead position slightly decreased heat inputs have to be used in comparison to the flat welding position.

The provided analysis (linear regression, Fig. 4 to Fig. 6), and given simple models for prediction of penetration, dilution and reinforcement, may be used for optimization and selection of desired heat input, i.e. essential welding parameters. Models can also be used to achieve required fillet weld size (either leg or throat thickness) by using proper heat input.

Some well-known benefits of pulsed GMAW are confirmed, particularly regarding less heat input required for achieving the same size fillet welds in comparison to regular GMAW. This can be beneficial, since lower heat input is desirable for better control of residual stresses and distortion.

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