Materials participation in welded joints manufacturing

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Abstract. Management of materials dilution to form a joint with higher features asked by complex metallic structures is a problem that took attention and efforts of welding processes researchers and this communication will give a little contribution presenting some scientific and experimental results of dilution processes studied by Welding Research Group from Iasi, Romania, TCM Department. Liquid state welding processes have a strong dependence related to dilution of base and filler materials, the most important are for automatic joining using welding. The paper presents a review of some scientific works already published and their contributions, results of dilution coefficient evaluation using weighing, graphics and software applied for shielded metal arc welding process. Paper results could be used for welders’ qualification, welding procedure specification and other welding processes researchers’ activities. The results of Welding Research Group from Iasi, Romania, TCM Department, show dilution coefficient values between 20-30 % of base material and 70-80 % of filler material for studied welding process.

1. Introduction
The dilution represents metallurgical phenomenon which permits combination of two materials, generally in liquid state, both after crystallization will form together a new material. Exemplification in the case of welding processes it is the forming of welded bead where two materials, base and filler metals, in different shapes, are melted with a heat source as is presented in figure 1 and after solidification will have different chemical and mechanical characteristics. The most used geometric form of filler materials is rod like but the geometric form of base materials are different because of edge preparation that always need to be clean, with specific sections manufactured using in the most cases grinding, cold deformation or thermal cutting. The heating source is specific for each welding process but could be considered that electric arc is most used nowadays. Speaking about welding processes the specialists know that it cover many processes that are:

- thermal cutting with lasers, thermal plasma or gases;
- joining processes with chemical adhesives, metallic alloys under and above 450 °C (brazing and soldering);
- solid state welding processes
- liquid state welding technologies,
- thermal spraying (metallisation);

Codification of all processes made by American Welding Society or by International Institute of Welding is around 200 in industrial use all over the world.
In welding processes that use like heat source the electric arc, the base and the filler materials are melting together to form a liquid bath. It is important for the welding engineer to know the dimensions and the composition of it, because these are important facts acting in future development of internal structures in weld metal, the transformation induced by heat in affected zone.

For one pass arc welding the dilution coefficient is presented like a proportion between the sections of filler and base material given by formula:

\[ KB = B/(A + B) \]  

where: B represents the base material participation and A is the participation of filler material. Here must be said that this formula is too general to describe entirely the phenomenon. More precise is the work with two coefficients: the first for filler material participation and the second for base material participation. This will be better because we have the opportunity to verify both formulas with the connection relation 2:

**Figure 1.** Liquid and solid state welding phases: a. liquid state; b. solid state. 1 heating source; 2 filler material; 3 electric arc column, 4 base materials, 5 materials melted bath, 6 future welded point.

**Figure 2.** Cross section of welded bead: A filler material participation, B base material participation.
\[ KB + KA = 1 \]  

Details for presented formula are shown in figure 2, where: A - filler material participation to welded bead manufacturing can be covered electrode or wire; B - base materials participation with edges geometrical forms in I, V, Y, X.

2. Scientific papers focused on dilution in welding processes

In their paper [1] the authors DuPont and Marder used gas tungsten arc welding (GTAW), plasma arc welding (PAW), gas metal arc welding (GMAW) and submerged arc welding (SAW) processes to study dilution in single pass welding for the type 308 stainless steel filler metal deposited onto 6.4 mm-thick A 36 carbon steel. They considered four parameters to evaluate the dilution using symbols V, I, S and Vfm and found dependence presented in (3):

\[
PctD = \left[ 1 + \frac{VfmEs}{(\eta fm - VfmEfm)} \right]^{-1} \times 100
\]  

Have been used following symbols: PctD = dilution percentage; V = voltage; I = current; S = welding speed; Vfm = volumetric filler metal rate; Es = melting enthalpy of substrate; \( \eta fm \) = melting efficiency that authors derived using (4):

\[
\eta fm = Aexp(-BE\alpha E/VIS\nu I)
\]  

where: A = 0.5 and B = 175 experimentally determined constants; \( \alpha \) = thermal diffusivity; \( \nu \) = kinematic viscosity of melting point. Authors presented a diagram showing the effect of processing parameters on dilution with experimental data for PAW, GTAW, GMAW and SAW welding processes.

The authors: Nouri M, Abdollah Zadeh A and Malek F studied [2] effect of pulsed gas metal arc welding (GMAW) variables on the dilution and weld bead geometry in cladding X65 pipeline steel with 316L stainless steel. The team used full factorial experiments method to study the effects of wire feed rate, welding speed, distance between gas nozzle and plate, and the vertical angle of welding on dilution and weld bead geometry. The results they get show that the dilution of weld metal and its dimensions (width, height and depth) increase with the feed rate, welding speed has an opposite effect for dilution. In the experimental part they used pulsed synergy GMAW process to clad wire 1.2 mm in diameter of 316L stainless steel onto a base material type X65 pipeline steel in plate form with: 15 mm thick, 100 mm wide and 200 mm long. The shielding gas was argon +2.5% CO\(_2\) at a flow rate of 15 L/min, electrode positive polarity. The resulting test pieces were sectioned, polished and etched in 2% natal, using digital photographs the dimensions of bead width \( w \), bead height \( h \), depth of penetration \( t \), angle of contact \( Z \) and dilution \( D \) were calculated with a computer software. Experimental results show that dilution \( D \) increases with increasing both wire feed rate \( f \) and welding speed \( s \) also if the quantity of heat given by arc power increases, more base material will contributes to liquid melted bath formation. The equations (5), (6), (7), (8) and (9) have been presented by researchers that could contribute to estimate geometrical features of welded bead manufactured with liquid state welding processes.

\[
w = 5.48 + 0.90f - 0.08s - 0.14(0.57f - 3.57)^2 + 0.81(s/20 - 5/2)^2 - 0.25(0.57f - 3.57)(s/20 - 5/2) + \]

\[
h = 2.44 + 0.16f - 0.02s + 0.08(0.57f - 3.57)^2 + 0.32(s/20 - 5/2)^2 - 0.04(0.57f - 3.57)(s/20 - 5/2) + \]
Kumar V, Lee C, Verhaeghe G, Raghunathan S researchers at The Welding Institute, UK presented [3] results about influence of welding process and parameters on dilution and corrosion resistance manufacturing and testing Alloy 625 weld overlay with different degrees of dilution, on a C-Mn steel substrate material. They evaluated the dilution in Conventional TIG welding, Hot wire TIG welding, TIG welding variant known as TOPTIG, MIG welding with globular transfer, pulse transfer, and spray transfer, MIG welding with electronically controlled short circuit transfer (STT). Main conclusions of researchers were: i) For the same heat input the higher current and higher welding speed produced substantially higher weld dilution. The researchers presented the example: 148A at 80 mm/min welding speed and 208A at 120 mm/min welding speed results in approximately the same heat input; the dilution at 148A welding current was only about 20% compared to 50-60% measured at 208A welding current; ii) Teams’ results of MIG welding experiments showed to be similar at a higher deposition rate; iii) In TIG processes dilution, depending on the process parameters, the dilution can be as low as 10% or as high as 70%. In MIG welding technologies, the dilution was generally less than 40%; iv) In arc welding, the dilution increased with increase in welding current and welding speed. An increase in heat input with increase in current increased the dilution but an increase in heat input due to decrease in welding speed reduced the dilution.

Plasma transferred arc welding (PTAW) has been used by researchers Deenadayalan K, Balaguru S, Velamurali, Chellapandi P [4] to deposit Colmonoy over SS-316 LN as hard faced coating in reactor applications. Hardness survey, base metal dilution and fusion line width were analyzed for different welding speeds: 1.5 mm/sec, 2.0 mm/sec, 2.5 mm/sec and 3.0 mm/sec. Authors assume that the melting of base metal and the subsequent mixing with filler metal causes the final chemistry of the weld deposit that could be approximated by: \[ 	ext{Dilution} \% = \text{Area of parent metal melted} / \text{Total area of fused metal} \]. The areas of weld beads are measured using image analysis software. Following data have been presented by researchers: For 1.5 mm/sec Total fusion area = 149.09 mm\(^2\); Base metal melted area = 54.84 mm\(^2\); Dilution \% = 36.24 \%; these dilution percentages could be used to evaluate final weld composition using: \[ X_x = X_A \% + X_F \% \text{ of filler metal dilution} \]. Where; \( X_x \) = average percentage of element X in the weld, \( X_A \) = percentage of element X in the base metal A, and \( X_F \) = percentage of element X in the filler metal F. For the main elements they get: Iron 21.97; Chromium 15.37; Nickel 55.86.

Om H and Pandey S have studied [5] effect of heat input on dilution and heat affected zone for submerged arc welding process collecting data about: wire feed rate (WFR), open circuit voltage (OCV), welding speed (WS) and electrode polarity (PO). Direct current constant voltage power source and mechanized submerged arc welding equipment with a current capacity of 600 amperes was used to deposit beads on 250 mm \( \times \) 75 mm \( \times \) 10 mm mild steel plates, electrode of 3.15 mm diameter and acidic flux (AWS SFA A-5.17) was used. After cooling at room temperature each plate was cut to see cross section and the etched specimens were then scanned using high resolution scanner to identify welded bead profiles and area of HAZ (heat affected zone) that were measured with digital measuring tools. The equation (10) has been presented by researchers with symbols already presented:

\[
\begin{align*}
\text{Dilution} \% & = \frac{s}{20 - \frac{5}{2}} f - 0.02s - 0.06(s/20 - 5/2)^2 + \\
& \quad 0.10(s/20 - 5/2)^2 - 0.12(s/20 - 5/2) \\
\end{align*}
\]
Coniglio N, Cross C E, Michael T and Lammer M worked to define a critical weld dilution to avoid solidification cracking in Aluminum [6] searching a relationship between filler metal dilution, local strain rate conditions, and cracking susceptibility when arc welding 6060 aluminum was used. Welding process was the gas-tungsten arc, cold wire feed process (GTAW-CWF). Weld test pieces 120 mm in length were cut from 40 × 4 mm extruded bars of 6060-T4, with a hardness of 40 HV0.5. The critical strain rate to form cracks was compared for several different filler metal dilutions: 0, 5, 9, 11, 14, and 16% 4043, calculated using relation: filler dilution = (B + C)/(A + B + C) × 100%, where A is the cross-sectional melted area of the 6060 base metal, and B+C is the difference between the total area of the weld metal and A. Main conclusions of authors were: 1 Observation of weld metal microstructure from the top surface reveals stray centerline grains for autogenously welds (i.e., with no 4043 filler added). These stray grains are no longer observed with 5% filler dilution. 2 Metallographic transverse cross sections taken from the weld mid length were examined for all 4043 dilutions, and weld bead dimensions were measured, weld cross sections made on 6060 coupons with 0 and 16% 4043 dilution showing an increase in weld bead thickness from 4.2 to 5.0 mm and only a slight increase in bead width. 3 Cross-sectional areas also increased with dilution and over bead curvature changed from –0.068 (concave) to +0.011 mm (convex), it occurred between 11 and 14% filler dilution. Increasing 4043 dilution from 0 to 16% decreases the mean grain size from 63 to 51 micrometers Increasing 4043 dilution from 0 to 16% decreases the mean cooling rate during solidification from 114 to 94°C/s. 4 For welds made with over 14% dilution, no cracking was observed. Filler dilution was found to vary between 0 and 16% for welding wire speeds between 0.0 and 41.7 mm/s. Each dilution examined, showing that silicon content is the main compositional change when increasing 4043 dilution.

3. Experimental results
In this research shielded arc metal welding (SMAW codification by American Welding Society and 111 by International Institute of Welding, IIW/IIS) process have been used with a welding current source Technology Inverter 200, shielded electrode type E 6013 and test pieces in S275 SR EN 10025 steel that has no problems to be weld with all welding processes.

![Figure 3. Base materials edge preparation.](image)
material removal (root face thickness); The bevel angle for all root was 30° resulting a groove angle of 60°.

As is presented in Table 1 edges of test pieces have been prepared using grinding and milling procedures and a number of weld bead were deposed. In the table letters are geometrical forms of edges and s is the thickness of base material.

Table 1. Test pieces edge forms and weld bead deposition.

| s [mm] | b [mm] | c [mm] | φ 1 [mm] | φ 2- last [mm] | passes |
|-------|--------|--------|-----------|----------------|--------|
| I     | 5      | 10     | 20        | 2.5            | 2.5    |
| V     | 10     | 5      | 4         | 3.25           | 4      |
| X     | 20     | 4      | 4         | 3.25           | 4      |

The first method used to evaluate dilution of base and filler materials was weighing and this have been done for base materials, initial and the part of electrode that remains after welding process was applied and finally the weighting of welded product. The results are presented in table 2.

Table 2. Using weighing to evaluate dilution.

| Base material weight [g] | Used electrodes [g] | Welded joint weight [g] | Base materials in weld [g] | Weld weight A+B [g] |
|--------------------------|--------------------|------------------------|---------------------------|---------------------|
| I                        | 190                | 12                     | 205                       | 3                   |
| V                        | 500                | 45                     | 570                       | 25                  |
| X                        | 1000               | 312                    | 1215                      | 285                 |

| KB = B/(A+B) | 0.2 | 0.35 | 0.19 |
| KA = A/(A+B) | 0.8 | 0.642 | 0.81 |
| KA + KB      | 1   | 0.992 | 1    |

The second method used to evaluate dilution of base and filler materials was measuring cross sections of test pieces. These have been grinding to small surface geometry and attacked with nital 5%. Hardness HV 0.1 has been used to estimate the welding area. A geometrical network was drawn taking account of initial test pieces edge forms and final welded joint. Dilution estimation was calculated using network characteristics presented in table 3. The network measurement was not done on cross section of welded bead; it was put on the paper using a magnification scale, also the welded bead identified with micro hardness measurement was only an evaluation. In the drawn cross section part of square forming network have been collected to evaluate area of filler material and area of base materials participated to manufacture studied welded joint. Main utilizations of
these methods to evaluate dilution were in students from Welding Engineering Program learning process in the field of Theory of Welding Processes because dilution is used to study different base materials welding, also for chemical composition evaluation of manufactured welded joints.

Table 3. Cross section area estimation to evaluate dilution.

|               | I  | V  | X  |
|---------------|----|----|----|
| Analysed cross section [mm$^2$] | 8  | 58 | 120 |
| Weld deposit area [mm$^2$] | 2.2 | 8.5 | 16 |
| Filler material area [mm$^2$] | 1.5 | 6.9 | 13.5 |
| Edge participation [mm$^2$] | 0.75 | 1.5 | 3.5 |
| Network [mm$^2$] | 4  | 9  | 9  |
| KB = B/(A+B) | 0.34 | 0.176 | 0.218 |
| KA = A/(A+B) | 0.681 | 0.811 | 0.85 |
| KA + KB | 1.021 | 0.987 | 1.0681 |

The third method to evaluate dilution of base and filler materials to form welded joint uses the software to draw cross section of welded joint and using “area” command this calculates dilution.

Figure 4. Software utilization to evaluate dilution.

4 Conclusions
In this paper author tries to show that research activity related to dilution in welding processes of Iasi TCM Welding group is connected with activity and scientific interests of prestigious welding groups from all over the world as have been shown in the reviews dedicated part, where researches of The Welding Institute from Cambridge United Kingdom, Lehigh University from United States
of America, Iran and India have been presented in short with their important results. Our results on dilution researches are dedicated and accomplished in our teaching activities together with students in Welding Engineering and all our three methods have in view to learn them about importance of dilution in liquid state welding, also we try to direct them to continue master and doctoral studies in Welding Specialisation supervised by other strong specialists of Iasi TCM Department.

The three methods to evaluate materials participation in welded joint manufacturing are very simple to practise, do not ask special investigation instruments and offer good results that could be used to study Schaeffler, DeLong and WRC diagrams for welding different base materials or high alloyed stainless steels.

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