Review of the weldability window concept and equations for explosive welding

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Abstract. Explosive cladding/welding is usually considered a solid state process in which the detonation of a certain amount of an explosive composition is used to accelerate one of the materials to be weld against the other in order to promote a high velocity oblique collision that will be responsible for bonding the materials. The conditions that should be met to achieve good welds define what is called as a weldability window or criteria. A weldability criterion based on the collision point velocity ($V_c$) and on the collision angle ($\beta$) is the most used today. In the $\beta$-$V_c$ space the weldability window is defined by four lines or limits. Despite of its wide used in explosive welding works, neither the concepts behind those limits neither the equations used to define them in the $\beta$-$V_c$ space are particularly clear. Contradictory concepts, and equations with undefined variables or parameters, are commonly found in the literature. This paper aims to clarify those concepts and equations through an integrated description of the weldability limits and a reviewed presentation of the associated equations with the variables and parameters, including their units, clearly defined. The reviewed concepts and equations are then used for the description of the explosive weld of stainless steel to carbon steel in cylindrical configuration.

1. Introduction: weldability window concept and equations

In the explosive technology area the conditions that should be met in order to achieve good welds define what is called the weldability window or criteria. A weldability criterion based on the flyer plate velocity and flyer mechanical properties developed by Cowan et al. [1] is mentioned by Mousavi and Al-Hassani [2], and is considered to give poor results. Criteria based only on the collision point velocity, although allowing the development of empirical equations to establish the weldability limits did not provide an overall picture of the process. At the present, the most used and well-known weldability criterion is based on the collision point velocity $V_c$, and on the collision angle $\beta$, as defined in figure 1.

In the $\beta$-$V_c$ space, the weldability window is defined by four lines or limits (see figure 2) being the first theoretical explanation for those limits given by Wittman [3].
There are four conditions for the establishment of those limits. The first limit is linked to the formation of a jet at the collision point; the rightmost line of the weldability window is a consequence of this condition. To meet this condition, some authors as Walsh et al. [4] stated that the $V_c$ should be smaller than the bulk sound speed $C_b$ (see equation (1)) of the materials to be welded while others, as Wiley et al. [5], state that $V_c$ should be smaller than $1.25C_b$ (see equation (2)). However, some other authors, as Abrahamsen [6], state that this limiting value for the $V_c$ is a weak function of the collision angle $\beta$ (see equation (3)), where $V_c$ is expressed in [mm/$\mu$s] and $\beta$ in [rad], so instead of a straight vertical line the rightmost limit of the weldability window should be a slightly concave left vertical line.

$$V_c < C_b$$

$$V_c < 1.25 \times C_b$$

$$V_c = \frac{\beta}{10} + 5.5$$

The second limit is related to the formation of a wavy interface; the leftmost line of the weldability window is a consequence of this condition. Kuzmin and Lysac (see [7] cited in [8]) state that this line, which defines the transition collision velocity $V_{c, tr}$, (above which we end up with a wavy interface), is a function of the collision angle; so, it should not be a straight vertical line. However, most authors consider it a straight vertical line and therefore independent of the collision angle. For its determination Cowan et al. [1] have proposed the equation (4) where $V_{c, tr}$, expressed in [km/s], appears as a function of the materials densities ($\rho_p$ and $\rho_f$, respectively for the density of the parent and flyer plate materials), expressed in [kg/m$^3$], Vickers hardness ($H_{V,p}$ and $H_{V,f}$), expressed in [MPa], and a critical Reynolds Number ($Re_{cr}$), that takes values between 8.0 and 13.0 for the asymmetric explosive welding configuration. Simonov [9], on the other hand, using the same kind of parameters but only the values referring to the harder of the materials, proposed a slightly different equation (see equation (5)) where $k_0$ is a dimensionless coefficient that is said to be approximately equal to 1.0 but reported as going up to 1.8 and where $V_{c, tr}$, $H_V$ and $\rho$ are expressed in, respectively, [km/s], [GPa] and [g/cm$^3$].

$$V_{c, tr} = \left( \frac{2Re_{cr} \left( H_{V,p} + H_{V,f} \right)}{\rho_p + \rho_f} \right)^{1/2}$$

$$V_{c, tr} = k_0 \left( \frac{H_{V,p} + H_{V,f}}{\rho_p + \rho_f} \right)^{1/2}$$
The third limit relates to the achievement of an impact velocity $V_p$, so that the impact pressure at the collision point exceeds the yield stress of the materials. The lower limit of the weldability window is a consequence of this condition. Deribas and Zakharenko, as mentioned by Zakharenko et al. [10], developed an equation for this limit (see equation (6)), in which the minimum collision point velocity $V_{c,min}$ is determined as a function of the Vickers Hardness $H_v$ [MPa] and of the density $\rho$ [kg/m$^3$] for the soften of the materials to weld, and as a function of the collision angle $\beta$ (in [rad]) and a constant $k_1$ that takes values between 0.6 (for clean surfaces), and 1.2 for imperfectly cleaned surfaces [11].

$$V_{c,min} = \frac{k_1}{\beta} \left( \frac{H_v}{\rho} \right)^{1/2}$$  \hspace{1cm} (6)

The fourth and final condition is to keep the impact velocity below certain a value so that the dissipation of kinetic energy should not produce a continuous melted layer on the materials which are to be welded. The upper limit of the weldability window is related with this requirement. Wittman [3] has developed an equation for the maximum impact velocity that avoids the formation of an interfacial melted layer from which, using the relationship that can be established between the impact velocity and the collision point velocity (see figure 1), it is possible to find the equation (7), where $\beta$ [rad] is the collision angle, $h$ [cm] is the thickness of the flyer plate, $V_c$ [cm/s] is the collision point velocity and $K_W$, a parameter essentially dependent on the physical and thermal properties of the flyer plate (see equation (8)) like the melting temperature $-T_m$ [°C], the bulk sound speed $-C_b$ [cm/s], the thermal conductivity $-k$ [erg/s.cm.°C], the constant pressure specific heat $-C_p$ [erg/g.°C], the density $-\rho$ [g/cm$^3$] and a constant $-N$ that is referred by Roset [12], but not verified, to take the value of 0.11 for several metals.

$$\sin \left( \frac{\beta}{2} \right) = \frac{K_W}{h^{1/4} V_c^2}$$ \hspace{1cm} (7)

$$K_W = \left[ \frac{(T_m C_b)^{1/2}}{2N} \left( \frac{k C_p C_b}{\rho} \right)^{1/4} \right]$$ \hspace{1cm} (8)

For the same propose, however, Deribas and Zakarenko come across with a slightly different equation (see equation (9)) where $\beta$, $h$ and $V_c$ have the same meaning as in equation (7) but $h$ and $V_c$ are now expressed in [m] and [m/s], respectively, and $K_{DZ}$ is a parameter now essentially dependent on the physical and mechanical properties (see equation (10)) like the elastic modulus $-E$ [N/mm$^2$], the Poisson coefficient $-\nu$ [-] and the density $-\rho$ [g/cm$^3$].

$$\sin \left( \frac{\beta}{2} \right) = \frac{K_{DZ}}{h^{1/4} V_c^{1.25}}$$ \hspace{1cm} (9)

$$K_{DZ} = \left[ \frac{1}{2} \left( \frac{E}{3(1-2\nu)} \right) \rho \right]^{1/2}$$ \hspace{1cm} (10)
2. Weldability window results and discussion
For the particular case of the stainless steel AISI 304L to low alloy steel DIN 50CrV4 (spring steel) welds, these limits, calculated using the equations 1 to 10 and the parameters values presented on the table 1, are shown on figure 3. Note that the units in which each parameter should be expressed to be used in the different equations are referred on the text and may be different from those on the table. The differences between the proposals for each one of the limits (except for the lower for which there is only one proposal) are significant, specially the one observed for the upper limit.

Table 1. Values of the several parameters used in the calculations of the different weldability limits.

| Variable                          | Units  | Value for the flyer plate | Value for the base plate |
|-----------------------------------|--------|---------------------------|--------------------------|
| $C_b$ – Bulk sound speed          | [cm/s] | 0.45x10^6                |                          |
| $R_{cr}$; Reynolds Critical      | [-]    | 10.5                      |                          |
| $H_{V,f}; H_{V,p}$ - Vickers Hardness | [GPa] | 1.491                     | 1.912                     |
| $\rho_f; \rho_p$ - Density       | [kg/m³] | 8030                      | 7872                      |
| $k_0$ – Empirical constant       | [-]    | 1.8                       |                          |
| $k_i$ – Empirical constant       | [-]    | 0.11                      |                          |
| $N$ – Empirical constant         | [-]    | 0.11 or 0.062             |                          |
| $T_m$ – Melting temperature      | [ºC]   | 1454                      |                          |
| $C_s$ – Specific heat            | [erg/g.ºC] | 5.00x10^6                |                          |
| $k$ – Thermal conductivity @500 ºC | [erg/cm.ºC.s] | 2.14x10^6                |                          |
| $h$ – Flyer plate thickness      | [cm]   | 0.15                      |                          |

Figure 3. Weldability window for the stainless steel AISI 304L and the low alloy steel DIN 50CrV4 welding system. Numbers on the different lines indicate the equations used for their definition or calculation (the upper limit sign with (8*) differs from the one sign with (8) on the value of the empirical parameter N; for the line (8) N takes the value of 0.11 and for the line (8*) N takes the value of 0.062. The open squares signed with the letter A to F refer to the welding conditions used by Mendes et al.. The interface of the weld obtain with those conditions are shown on figure 4.
Together with the several weldability limits, on the figure 3, are also plotted the weld conditions observed by Mendes et al. [13] for the stainless steel AISI 304L to low alloy steel DIN 50CrV4 system in a cylindrical configuration. All the welds conditions verify the lower weldability limit and the most restrictive of the right and left limits. However, in what refers to the upper limit, the weld conditions are all above or all bellow it depending if this limit is either evaluated using the Wittman condition (equations (7) and (8)) or the Deribas and Zakarenko condition, (equation (9) and (10)) respectively.

Nevertheless, the morphology of the interface of those welds, shown on figure 4, indicate that at least the welds B to F, that present extensive zones, some time even continuous (eg. weld F), of melted and solidified material, should be above the upper limit, as they are for the Wittman condition. However, for the weld A, the zones of melted and solidified material are almost absent, and this welding condition should be bellow the upper limit. This possibility can only be achieved, while keeping the other welding conditions above this same limit, if on the equation (8) the value of the empirical constant $N$ is taken equal to 0.062.

**Figure 4.** Morphology of the welds interfaces for the welding conditions shown on figure 3 as open squares named from A to F.

### 3. Conclusion

The weldability window concept was revisited. The physical ideas associated to each one of its four limits were reviewed and alternative equations, proposed by different authors, for their definition were shown. Special care was put on the clarification of the meaning of each one of the variables and parameters of those equations as well as on the units in which those parameters or variables should be expressed. The so defined limits were cross checked with the experimental results of Mendes et al.
The most restrictive alternatives of all limits seem to apply better than the others. However, for the upper limit, the fit to the results was only achieved for the Wittman model and changing the value of its empirical parameter $N$ (see equation (8)) from what is referred in bibliography, $N = 0.11$ [12] but, in fact, was never verified experimentally [14], to something slightly different: $N = 0.062$.

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