Review of the weldability window concept and equations for explosive welding

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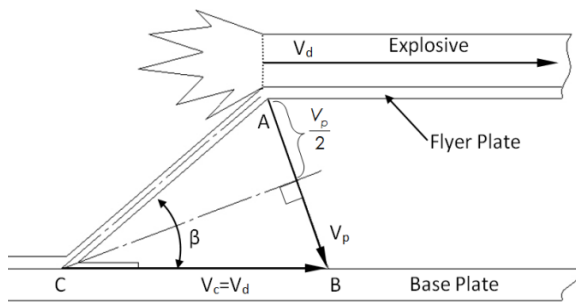
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Abstract. Explosive cladding/welding is usually considered a solid state process in which the detonation of a certain amount of an explosive composition is used to accelerate one of the materials to be weld against the other in order to promote a high 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 criteria based on the collision point velocity (V_c) and on the collision angle (β) is the most used today. In the β-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 β-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.

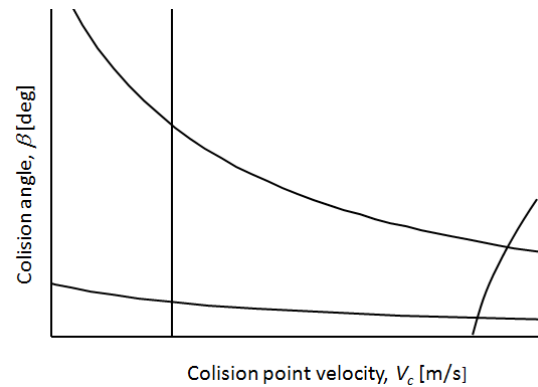## 1. Introduction: weldability window concept and equations

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 β, as defined in figure 1.

In the β-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].

Figure 1. Schematic representation of the explosive welding process.

Figure 2. The weldability window concept and limits in the β-V_c space.

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 $1.25 C_b$ (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 β (see equation (3)), where V_c is expressed in [mm/µs] and β in [rad], so instead of a straight vertical line the rightmost limit of the weldability window should be a slightly concave left vertical line.

$$V_c < C_b \tag{1}$$

$$V_c < 1.25 \times C_b \tag{2}$$

$$V_c = \frac{\beta}{10} + 5.5 \tag{3}$$

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 (ρ_p and ρ_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 ρ are expressed in, respectively, [km/s], [GPa] and [g/cm^3].

$$V_{c,tr} = \left(\frac{2 Re_{cr} \left(H_{V,p} + H_{V,f} \right)}{\rho_p + \rho_f} \right)^{1/2} \tag{4}$$

$$V_{c,tr} = k_0 \left(\frac{2 \times H_V}{\rho} \right)^{1/2}$$

(5)

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 el at. [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 ρ [kg/m^3] for the soften of the materials to weld, and as a function of the collision angle β (in [rad]) and a constant k_1 that takes values between 0.6 (for clean surfaces), and 1.2 for imperfectly cleaned surfaces [11].

$$V_{c,min.} = \frac{k_1}{\beta} \left(\frac{H_V}{\rho} \right)^{1/2}$$

(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 a 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 β [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 [ºC], the bulk sound speed – C_b [cm/s], the thermal conductivity – k [erg/s.cm.ºC], the constant pressure specific heat – C_p [erg/g.ºC], the density – ρ [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.

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

(7)

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

(8)

For the same propose, however, Deribas and Zakarenko come across with a slightly different equation (see equation (9)) where β, 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 oefficient ν – [-] and the density – ρ [g/cm^3].

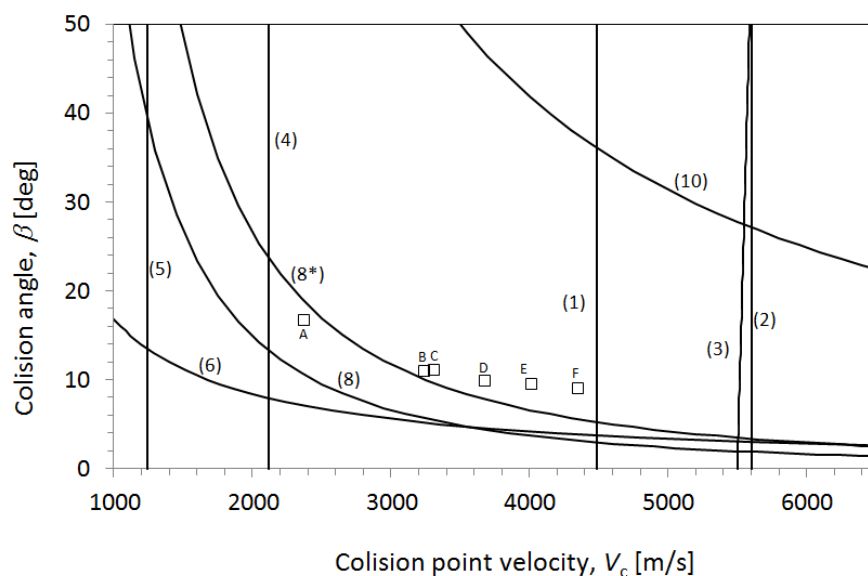$$\sin \left(\frac{\beta}{2} \right) = \frac{K_{DZ}}{h^{1/4} \, V_c^{1.25}}$$

(9)

$$K_{DZ} = \left[\frac{1}{2} \left(\frac{\dfrac{E}{3(1-2\nu)}}{\rho} \right)^{1/2} \right]$$

(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.
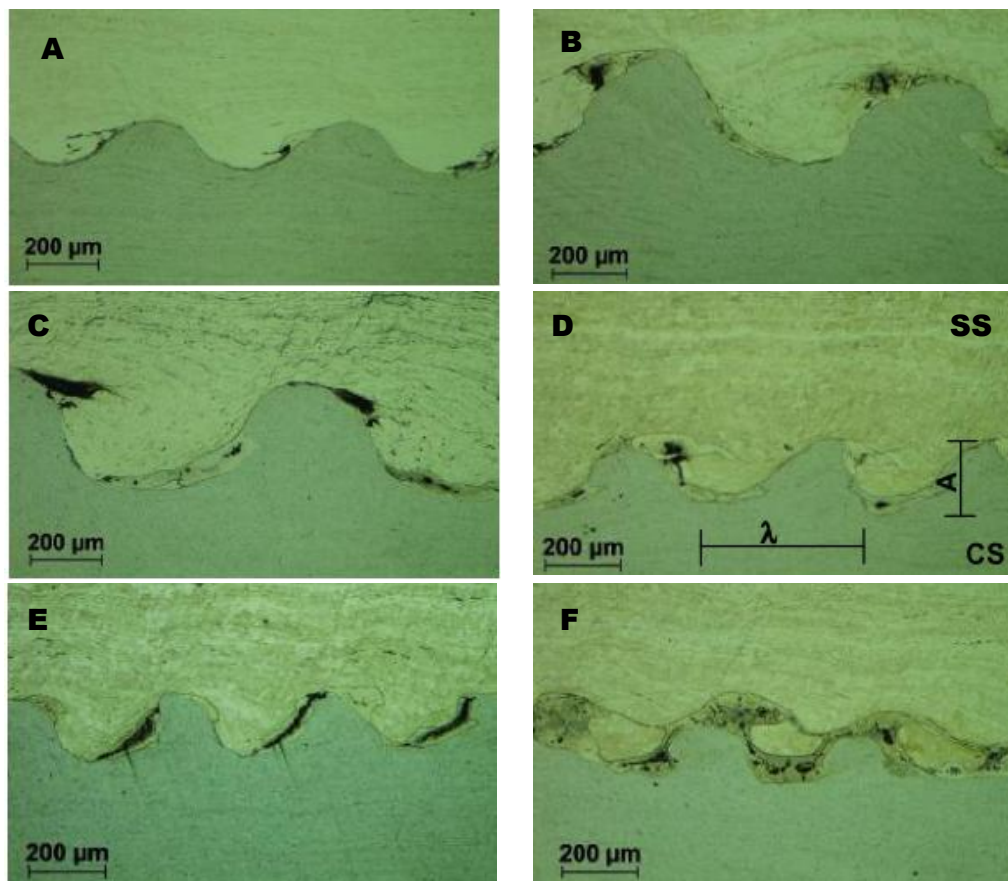
Variable	Units	Value for the flyer plate	Value for the base plate
C_b – Bulk sound speed	[cm/s]	0.45×10^6	-
Re_{cr}; Reynolds Critical	[-]	10.5	
$H_{V,f}$; $H_{V,p}$- Vickers Hardness	[GPa]	1.491	1.912
ρ_f; ρ_p - Density	[kg/m³]	8030	7872
k_0 – Empirical constant	[-]		1.8
k_1 – Empirical constant	[-]	0.11	
N – Empirical constant	[-]	0.11 or 0.062	-
T_m – Melting temperature	[ºC]	1454	-
C_p – Specific heat	[erg/g.ºC]	5.00×10^6	-
k – Thermal conductivity @500 ºC	[erg/cm.ºC.s]	2.14×10^6	-
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 *at 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*.

[13]. 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: $N = 0.062$.

References

[1]   Cowan G, Bergmann O and Holtzman A 1971 Mechanism of bond zone wave formation in explosion-clad metals *Metall. Mater. Trans.* B **2** 3145-55

[2]   Akbari Mousavi A A and Al-Hassani S T S 2005 Numerical and experimental studies of the mechanism of the wavy interface formations in explosive/impact welding *J. Mech. Phys. Solids* **53** 2501-25

[3]   Wittman R H 1973 *Proc. of the 2nd Int. Symp. on the Use of Explosive Energy in Manufacturing* (Marianskie Lazni, Czechoslovakia) pp 153-168

[4]   Walsh J M, Shreffler R G and Willig F J 1953 Limiting Conditions for Jet Formation in High Velocity Collisions *J. Appl. Phys.* **24** 349-59

[5]   Wylie H K, Williams P E G and Crossland B 1971 *Proc. of the 3rd Int. Conf. of the Center for High Energy Rate Forming* (Denver, CO) pp 1.3.1-1.3.43

[6]   Abrahamson G R 1961 Permanente periodic surface deformation due to a travelling jet *J. Appl. Mech.* **83** 519-28

[7]   Kuzmin S V and Lysak V I 1991 *Inter-Departmental Transaction Explosive Welding and Properties of Welded Joints* (Volgograd, Russia: Volgograd Polytechnic Institute) pp 29-38

[8]   Lysak V I and Kuzmin S V 2012 Lower boundary in metal explosive welding. Evolution of ideas *J. Mater. Process. Tech.* **212** 150-6

[9]   Simonov V A 1991 Binding criterion for metals with explosive welding *Combust. Explo. Shock* **27** 121-3

[10]   Zakharenko I and Zlobin B 1983 Effect of the hardness of welded materials on the position of the lower limit of explosive welding *Combust. Explo. Shock* **19** 689-92

[11]   Zamani E and Liaghat G H 2012 Explosive welding of stainless steel-carbon steel coaxial pipes *J. Mater. Sci.* **47** 685-95

[12]   de Rosset W S 2006 Analysis of Explosive Bonding Parameters *Mater. Manuf. Process.* **21** 634-8

[13]   Mendes R Ribeiro J B and Loureiro A 2013 Effect of explosive characteristics on the explosive welding of stainless steel to carbon steel in cylindrical configuration *Mater. Design* **51** 182-92

[14]   Carpenter S H and Wittman R H 1975 Explosion Welding *Annu. Rev. Mater. Sci.* **5** 177-99