

Three-Stage Character Of Molten Metal Drop And A Hard Substrate Contact Interaction

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Abstract. The paper presents the results of theoretical and experimental studies of the interaction between a molten metal drop and a solid metal substrate and justifies measures to avoid or to weaken this interaction.

Introduction

Welding in carbon dioxide is a key process in all branches of industry both in our country and abroad [1]. A significant drawback of welding in CO₂ is high metal splashing, as the result; the surface of the product to be welded is covered with metal spatter. The mechanism of metal spray cohesion with the surface is studied in works [2, 3, 4, 5]. However, further developing and supplementing the theory of spray interaction with the surface support improvement of the shielding means and the quality of products, in particular when manufacturing welded structures of low and medium alloy steels, producing mining equipment, main pipelines etc. Drops of various sizes are splashed when welding in CO₂.

Small spatter ~ 0.02 mm leaves the zone of welding with the speed ~ 40 m/s. The angle of its direction and the perpendicular to the surface of the product to be welded does not usually exceed 25°. The bigger spatter (diameter > 1 mm) move slower with bigger opening angle. As the rule, the surface of the products to be welded is covered with big and small spatter, while the nozzle and the neck of the torch with small spatter only.

Main part

The drop contacts with the surface to be welded over three stages: 1) physical contact appears, id. atoms of contacting surfaces are approaching each other, so physical or slight chemical interaction is possible; 2) activation of the contact surfaces (generation of active centers); 3) bulk interaction.

The third stage is distinguished by the growth of interaction both in the plane of the contact attended by generation of strong chemical bonds and around the contact zone. This process occurs in the active centers, which are fields of elastic lattice distortion, or defects of the structure (dislocations, vacancies etc) and is over under coalescence of discrete areas of interaction. The third stage of molten metal drop – product surface interaction is completed in conditions of recrystallization, causing generation of common grains in the contact zone.



The quantity of heat in a drop with the diameter D_d , is equal to q when escaping from the arc space. The drop loses some heat q_{TO} , used for convection and radiation when moving to the surface of the product. At the moment of contact the quantity of heat in the drop is q_k . Temperature distribution ΔT , depending on heat content of the drop is registered in the area where a drop of the diameter D contacts with the surface (the diameter of interaction D_x).

A high speed of the drop (40 m/s and above) is the cause of high pressure in the contact zone. It is known that the drop leaving the arc space is over-heated; its temperature can come up to 2500°C. High temperature of the contact (T_{cont}) and pressure are important factors of physical and chemical interaction, providing strong drop-surface joining. There is a physical contact between them due to deformation and drop spreading. As the temperature of drops is high and their surface gets deformed, their atoms in the contact zone are excited and tend to form active centers of chemical interaction.

As the result of colliding with the surface, the drop gets deformed, furthering their physical contact. Pressure P is typical for the zone of collision, being component of the total pressure P_t (or dynamic component) and impact pressure P_i , arising due to the effect of a hydraulic shock.

First, liquid volume of the drop is elastically deformed in the zone of drop colliding with the surface. In a time interval $t_y = d/c$ (c – sound speed in the melt, m/s), equal 0.1 microsecond for small and 1.0 microsecond for bigger drops, and sufficient for the shock wave front (moving from the place of its colliding with the product) to reach the free surface of the drop, a thin and flat liquid layer of spreading drop is formed due to its cushioning. Then the drop gets deformed uniformly. The maximal impact pressure is calculated according to the formula below:

$$P_y = \frac{\mu}{2} \cdot \rho_0 V, \quad (1)$$

where μ – stiffness coefficient of the drop, based on the relaxation capacity of the drop liquid, depending on its impact velocity and form; ρ – density of the melt, kg/m³; V – speed of the drop at the moment of impact, m/s.

The difference of the impact pressure for different diameters of drops is revealed on the base of calculations done for the case above: it is 30 MPa for small drops and 10 MPa for bigger drops, respectively. The total pressure of the drop, calculated by Bernuolli's equation $P_H = \rho \cdot V^2$, is 10 MPa for small drops and 7 MPa for bigger ones.

Provided that the height of the drop decreases evenly from d to h along its axis over the period of deformation, having the speed V of drop movement at the point of impact, the total pressure depends on the time of drop deformation $t_H = \frac{d-h}{V}$, which is 10 microseconds for small and 4 microseconds for bigger drops.

A high impact pressure furthers cleaning of the product surface at the point of impact and causes a physical drop – product contact. The total pressure, acting over the complete period of deformation and hardening of the drop, supports its stronger cohesion with the surface.

The drop deformation is caused by the kinetic energy of movement when hitting against the surface. The crystallization front extends over the surface of the colder product simultaneously with drop spreading. The drop deformation is completed when the crystallization front meets the free surface of the drop. As the process of deformation is over the diameter of drop interaction with the surface is maximal.

The temperature in the contact (temperature of the contact T_{cont}) of the surface (substrate) with a liquid, fast-spreading drop is somewhere between the temperature of the substrate T_s and temperature of the drop T_k ($T_k > T_{cont} > T_s$), being constant for the period t_0 , which is equal to the period of drop crystallization.

The drops, welded completely on the surface are hard-to-remove, since their removal requires special tools. The criterion of hard removability is a specific force of shear P_{sh} , which is necessary for removal of such drop.

Components with various degrees of surface roughness are used in manufacturing welded products. Further theoretical and experimental research requires the use of products with following degrees of roughness: as delivered, $R_a=1.69 \mu\text{m}$; sand jet processed surface, $R_a=7.73 \mu\text{m}$, and the surface processed with a sanding disk, $R_a=16.4 \mu\text{m}$.

For the purpose of research a bead joint is made on the samples of steel St3 (GOST 380-85) with various degrees of roughness. The conditions of experiment are as follows: welding in CO_2 , a semi-automatic device ПДГ-508 (semi-automatic arc welding in active gas), power source WRV -506, wire СБ-08Г2С (GOST 2246, composition: C – 0.08%, Si – 1%, Mn – 2%) with the diameter of 1.6 mm, current 300...320 A, arc voltage 30...32 V.

The most hard-to-remove spatter is detected on the surface processed with a sanding disk, while the surface as delivered is covered with the least spatter. However, the biggest diameter of interaction D_x is identified on the surface as delivered. In the process of carrying out the research into the spatter cohesion with the pre-heated metal surface a dependence of its strength on T_s and T_{cont} (Fig. 1) is revealed, the interaction diameter D_x of a drop (diameter D) with the surface is increased. The worth

variant is described by the equation $\frac{D_x}{D} = 1$.

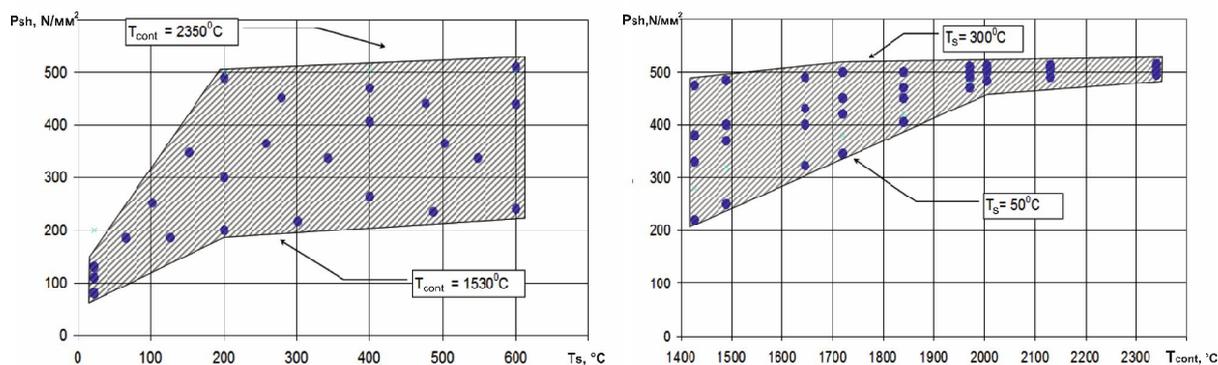


Figure 1- Influence of the substrate temperature T_s and temperature of the contact T_{cont} on the shear pressure P_{sh}

However, theoretical and experimental data on the kinetics of drop spreading over the surface of the product to be welded, obtained in terms of the methods available [1, 6, 7, 8], point at the smallest interaction diameter (D) of molten metal drops with the surface processed by a sanding disk, and at the biggest one with the surface as delivered. The most hard-to-remove drops are detected on the surface processed by a sanding disk; therefore, the cohesion strength of a drop with the surface does not depend on the diameter of their interaction only. This fact can be referred to the processes of contact interaction of molten metal drops with the surface to be welded.

A metallographic analysis of microstructures in the interaction zone is carried out to determine the character of this interaction. The main component of the oxide film on the surface of the drops is FeO . When drops contact with the dross-coated surface of metal, it melts. The oxide film of spatter contacts with the dross of the welded surface in the melt, so cohesion is less strong (P_{av} amounts to 20-50 N/mm^2). The space between the weld and the contact zone influences P_{av} in particular, and since the product is not heated evenly when welding, so one can affirm that cohesion strength of a drop with the surface depends on T_s .

Having studied the cohesion of bigger drops it is revealed their fusion with the surface is possible provided that oxide films are removed or the contact zone is absolutely free of them. The fusion process is regarded to be over when metallic bond is formed totally over the interaction zone, and P_{av}

gets constant ($P_{av} \approx 500 \text{ N/mm}^2$ – see Fig. 1). However, one should take into consideration cohesion strength depends on the intensity of heat removal, contact and surface temperatures, impact pressure at the moment of contact and oxides on the surface. All these factors further complete or partial fusion of interacting drop and surface. P_{av} varies 60 to 500 N/mm^2 . Moreover, rising temperature of the surface is the cause of a longer drop liquid state; then the temperatures get equal due to the intensity of heat removal (Fig. 2).

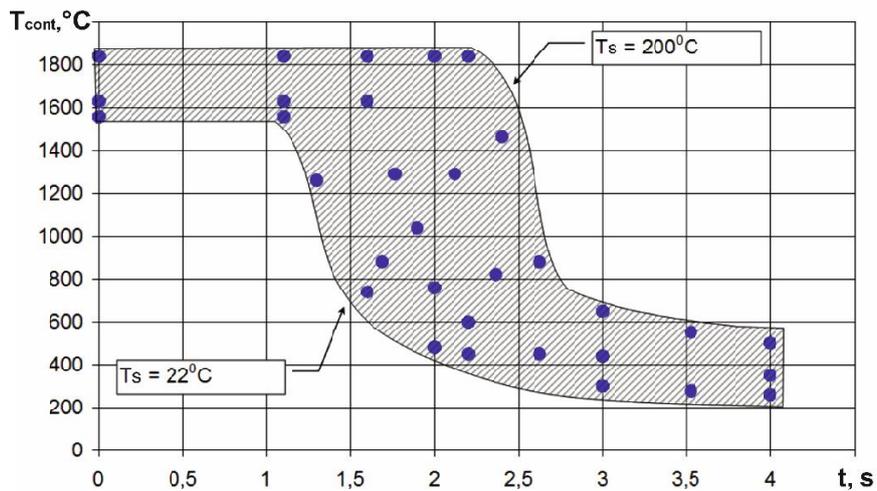
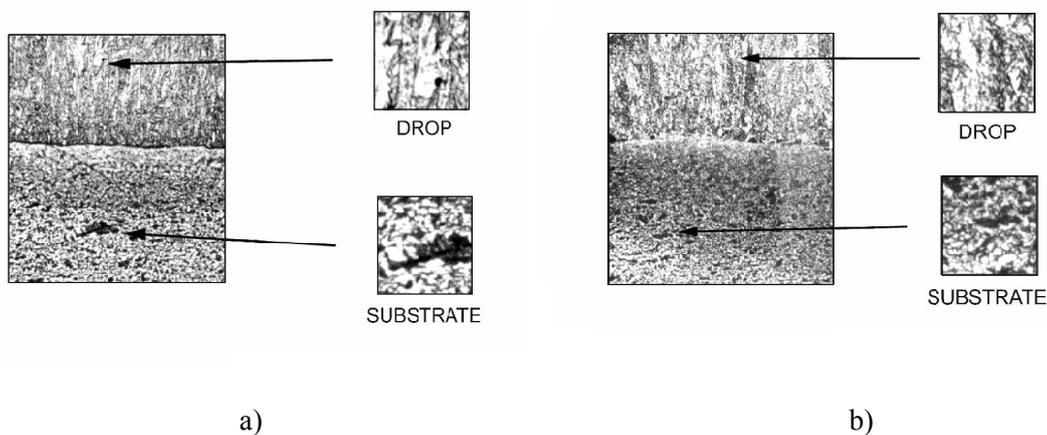


Figure 2 - The contact thermal cycle regarding the substrate temperature T_s

The strength of drop cohesion with the surface depends both on its cleanness and roughness. Higher roughness increases, first, the temperature of contact under the spatter, since the temperature of roughness peaks is high because of insufficient heat removal, second, the total interaction area of drop and surface atoms.

Welded samples made of steel Ct3 with various degrees of roughness are tested to confirm theoretical backgrounds. Macro- and micro-sections are made on the point of spatter and surface contact, optical microscope MIM -7 is used for the purpose of research, providing 100 – 500 x magnification. The microstructures are shown in Figure 3. The results of processing experimental data are given in Table 1.



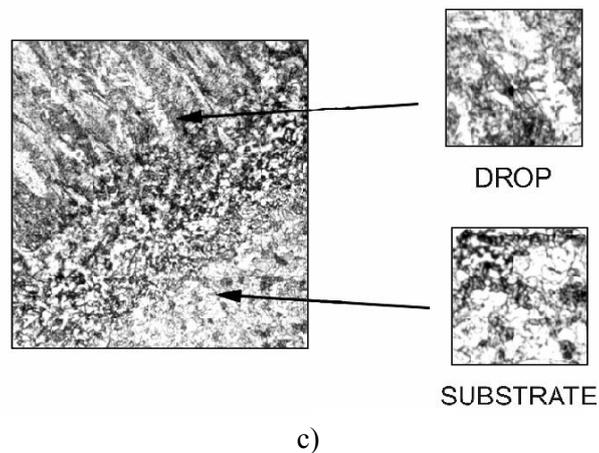


Figure 3 - The microstructure of drop and surface contact zone: a) – the sample as delivered, b) – sample processed in a sand jet chamber, c) – sample processed with a sanding disk (x150, leader – computer magnification x300)

Table 1 - Microstructure analysis of drop and surface contact zone

Figure	Description of the structure
3 a	In the contact zone there is a layer of oxides and non-metallic impurities without obvious layer growth. The nature of interaction is fusion of drop oxides with the dross of the surface ($P_{av} - 20-40 \text{ N/mm}^2$).
3 b	In the interaction zone there is a boundary of the contact over the total length. The nature of interaction is partial fusion ($P_{av} - 100-150 \text{ N/mm}^2$, $l/D_x \approx 0.2$). On the left there are oxides and non-metallic impurities.
3 c	In the contact zone there are atoms of a drop fused with the substrate ($P_{av} - 500 \text{ N/mm}^2$, $l/D_x \approx 1$).

Note: In all cases under consideration the base metal consists of ferrite and perlite. The drop has a dendrite structure. The growth of dendrites is directed from the contact zone to the free surface of the drop.

Interaction is assessed relying on a non-dimensional quality l/D_x (l – length of fused sections), which influences P_{av} of this drop. Taking into consideration, that P_{av} is measured according to the drop with the area $S_{1/2} = \frac{\pi D_x^2}{8}$, the cohesion strength σ_{cs} is calculated by the

formula: $\sigma_{cy} = \frac{8P_{av}}{\pi D_x^2}$. The results are outlined in Figure 4.

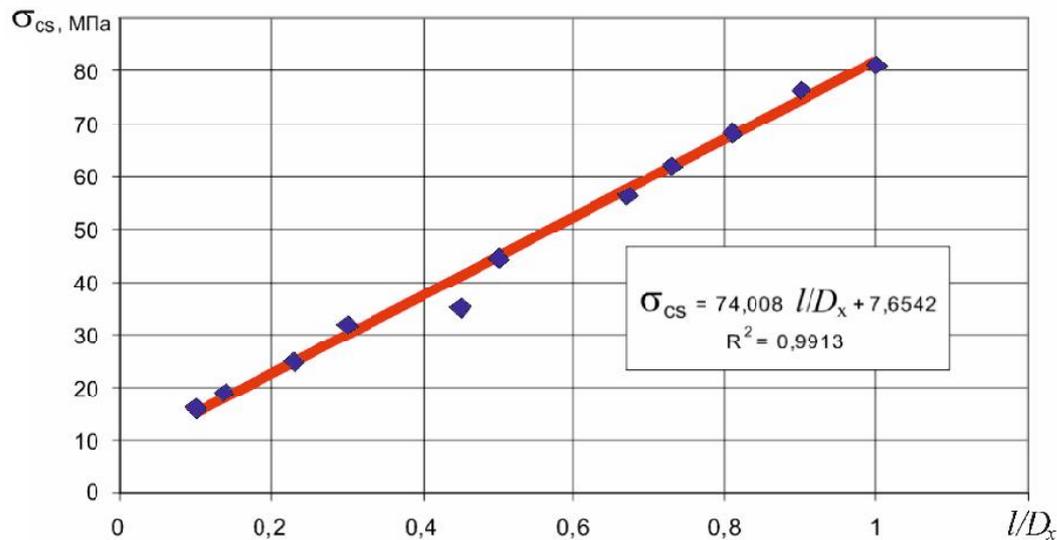


Figure 4 - l/D_x vs. cohesion strength σ_{CS}

Having analyzed the data of experiments it is revealed that the thickness of drop to surface interlayer influences P_{av} of this drop, being a direct proportion, when the drop contacts with the dross-coated surface as delivered.

The data of experiments are computer processed, a trend line is drawn and equation of the dependence of interlayer thickness on P_{av} is determined. It is found out the thicker is the interlayer, the smaller P_{av} . As P_{av} tends to 0 when thickness of the interlayer consisting mainly of FeO is 12 μm . The conditions reducing or eliminating harmful effect of factors, providing strong cohesion of molten metal drops with the surface, are required for its shielding.

Conclusions

1. Key factors are identified on the base of experiments, which influence the character of spatter (drops) interaction with the surface. The cohesion strength is affected by the intensity of heat removal, temperature of the contact (T_{cont}), temperature of the surface (T_s), force impact of the drop, and oxides on the surface and its roughness.

2. Having analyzed microstructures in the drop – surface contact zone, fusion of the spatter oxide film with the dross on the surface to be welded is revealed, and the least strong cohesion (P_{av} is 20-50 N/mm^2) is formed when drops contact with the metal surface. Fusion of bigger drops with the surface is possible provided that oxide films are removed from the point of contact. The fusion process is regarded to be over when metallic bond is formed totally over the interaction zone, and P_{av} gets constant ($P_{av} \approx 500 \text{ N/mm}^2$). However, the strength of cohesion is affected by multi-factorial character of contact interaction, resulting in partial or complete drop – surface fusion. P_{av} varies in that range 60 - 500 N/mm^2 . Interaction is assessed on the base of a non-dimensional quality l/D_x (l – length of the fused zones). The strict dependence of cohesion strength σ_{CS} on l/D_x is revealed.

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