

Effects of Surface Depression on Pool Convection and Geometry in Stationary GTAW

Arc pressure at peak duration produces deep penetration in pulsed current gas tungsten arc welding

BY S. H. KO, S. K. CHOI AND C. D. YOO

ABSTRACT. The effects of surface depression on pool convection and geometry in stationary GTAW are simulated numerically under DC and pulsed-current conditions. Welding current and Marangoni flow affect surface depression and velocity such that inward flow by the current and positive surface-tension gradient acts to decrease surface depression. Arc pressure is found to be a major factor in surface depression and in fluctuations of free surface and flow velocity. While arc pressure at the low current range has negligible effects on surface depression and pool geometry, it should be considered in the high current range. Under the pulsed current condition, deep penetration is produced mainly by arc pressure at peak duration. The solid-liquid interface profile at the pool center and periphery becomes similar to that of peak and base current, respectively, and penetration is closely correlated to surface depression.

Introduction

Because weld pool convection was found to have significant effects on the bead width and penetration in arc welding (Ref. 1), extensive research has been undertaken to reveal the relationship between pool convection and geometry (Refs. 2–10). Among the various factors affecting pool convection, electromagnetic force and surface-tension gradient are the most important. Because the electromagnetic force generates circulation within the molten pool in a downward direction, penetration increases by pool convection. The rotating direction of Marangoni flow depends on the surface-tension gradient, which is affected by minor elements such as sulfur composition in the base metal. These convection patterns with heat input from the arc determine pool geometry.

S. H. KO and C. D. YOO are with the Department of Mechanical Engineering, KAIST, Taejeon, Korea. S. K. CHOI is with the School of Mechanical Engineering, Kyungpook National Univ., Taegu, Korea.

Numerical methods have been employed to predict pool convection, and the calculated pool geometry was in agreement with the experimental result (Refs. 2, 5). One of the general assumptions made to simplify numerical computation is the molten pool surface is flat (Refs. 2–4). Another assumption of a deformed surface depression was employed (Refs. 6–8) using the surface profile in an equilibrium state by minimizing the potential energy (Ref. 9). Several attempts were made to include the free surface under the direct current (DC) condition (Refs. 10, 11). While three-dimensional pool geometry was calculated for nonautogenous welding using surface elevation, the effect of arc pressure was not considered (Ref. 10). A numerical model for a full penetration weld with two free surfaces was presented (Ref. 11). Because the focus was the Marangoni effect on a free surface, the effect of the electromagnetic force was ignored and the pool had a cylindrical shape. Therefore, dynamic effects of surface depression on pool convection and its geometry have not been fully understood under DC and pulsed-current conditions.

In this work, dynamic variations of surface depression and pool convection in DC and pulsed-current gas tungsten arc welding (GTAW) are calculated numerically by employing the Volume of Fluid (VOF) method (Ref. 12). The solid-liquid interface of a molten pool is computed by solving the energy equation,

and the effects of arc pressure, current and surface-tension gradient on surface depression and convection are analyzed based on the calculated results. Causes of deep penetration by the pulsed current are also simulated.

Formulation

Since the effects of a free surface are emphasized in this work, the following assumptions are made in the formulation: 1) fluid flow in the axisymmetric molten pool is incompressible and laminar, 2) the effect of the drag force from the plasma jet is neglected, and 3) material properties are constant. The principle of the VOF method for calculating fluid flow with a free surface is described briefly because it was explained in detail in other works (Refs. 8, 12, 13). The solution domain is divided by the staggered grid and the function F is defined to describe the fluid volume ratio within the cell. The governing equations consist of the continuity, momentum equations and an additional equation relating to the function F as follows:

$$\bar{\nabla} \cdot \bar{v} = 0 \quad (1)$$

$$\begin{aligned} & \frac{\partial \bar{v}}{\partial t} + (\bar{v} \cdot \bar{\nabla}) \bar{v} \\ & = -\frac{1}{\rho} \bar{\nabla} P + \nu \nabla^2 \bar{v} \\ & + \frac{1}{\rho} \bar{J} \times \bar{B} + \bar{g} \beta (T - T_{liq}) \end{aligned} \quad (2)$$

$$\frac{\partial F}{\partial t} + (\bar{v} \cdot \bar{\nabla}) F = 0 \quad (3)$$

where \bar{v} represents the velocity vector, P the pressure, ρ the mass density, ν the viscosity, \bar{J} the current density, \bar{B} the magnetic flux, β the thermal expansion and T_{liq} the melting temperature. The electromagnetic and buoyancy forces in Equation 2 are included as the body force.

The energy equation is solved in an implicit manner to calculate the temperature and solid-liquid interface as follows:

KEY WORDS

Surface Depression
Pool Convection
GTAW
Direct Current
Pulsed Current
Marangoni Flow
Volume of Fluid Method

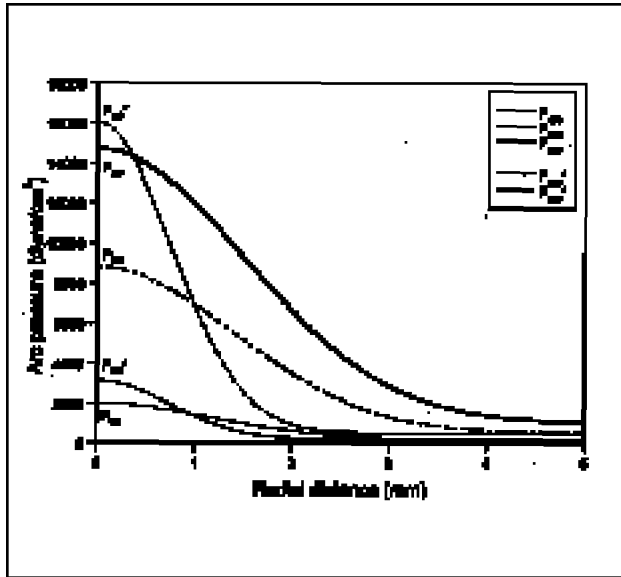


Fig. 1 — Arc pressure distributions on the pool surface.

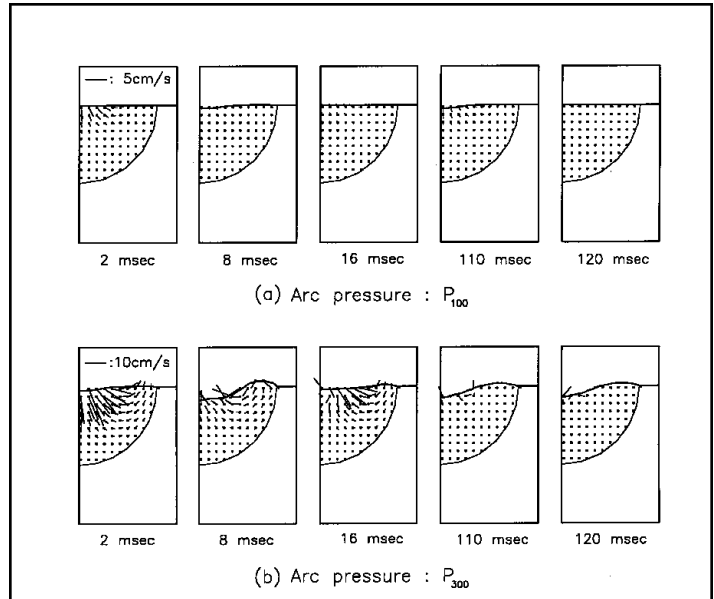


Fig. 2 — Surface depression and flow patterns for P_{100} and P_{300} . ($I = 0A$, $\sigma = 1200$ dyne/cm).

Table 1 — Material Properties of Mild Steel Used for Calculation

Mass Density,	7860 (kg/m ³)
Kinematic Viscosity,	5.6×10^{-7} (m ² /s)
Surface Tension Coefficient,	1200 (dyne/cm)
Surface Tension Gradient, $d\sigma/dT$	$\pm 4.9 \times 10^{-4}$ (N/mK)
Electrical Conductivity, σ_e	8.54×10^5 (mho/m)
Permeability, μ_0	4×10^{-7} (H/m)
Thermal Conductivity, k	30 (W/mK)
Specific Heat, C_p	795 (J/kgK)
Latent Heat of Fusion, H	272 (kJ/kg)
Liquidus Temperature, T_{liq}	1809 (K)
Solidus Temperature, T_{sol}	1789 (K)
Distribution Parameter of Current Density, r_j	3 (mm)
Distribution Parameter of Heat Flux, r_q	3 (mm)

with surface depression, they are assumed to be constant because these distributions are not known. Marangoni flow due to the surface-tension gradient, $(d\sigma/dT)$, is considered by imposing shear stress on the free surface as follows:

$$\tau = \frac{\gamma}{T} \frac{T}{\psi} \quad (7)$$

where γ and ψ denote the surface-tension coefficient and tangential direction of the free surface, respectively. The SOLA-VOF code written in FORTRAN is modified to include the effects of electromagnetic force and surface-tension gradient.

Results and Discussions

Effects of Welding Parameters under the DC Condition

In order to investigate the effects of the process parameters on surface depression and pool convection, the molten pool is assumed to be a hemispherical shape having a radius of 5 mm without solving the energy equation. Physical properties corresponding to those of mild steel are listed in Table 1 (Refs. 14,15). Initial flow velocity within the molten pool is set to zero. When the pressures of P_{100} and P_{300} are exerted on the surface without the current and surface-tension gradient, the calculated free surface profile and flow pattern are like that illustrated in Fig. 2. Small surface depressions and flow velocity are developed at P_{100} , and they continue to fluctuate until the steady state is reached, which represents

$$\rho C_p \frac{T}{t} + v T = k \nabla^2 T + \dot{q}_j \quad (4)$$

where C_p represents the specific heat, k the thermal conductivity and \dot{q}_j the joule heating per unit volume. The latent heat,

H , is considered by increasing the specific heat in the temperature range of phase change as follows:

$$C_p^* = \frac{H}{(T_{liq} - T_{sol})} + C_p, \quad T_{sol} < T < T_{liq} \quad (5)$$

As for the boundary conditions, the free-slip and no-slip conditions are imposed along the z -axis and on the solid-liquid interface, respectively. The arc pressure of a Gaussian distribution is exerted on the pool surface as shown in Fig. 1,

where P_{100} , P_{200} and P_{300} represent arc pressure at welding current 100, 200 and 300 A (Ref. 11). To compare the effect of arc pressure distribution, modified pressures of P_{100}^* and P_{200}^* are introduced that have the same total arc forces of P_{100} and P_{200} , respectively. The heat flux and current density from the arc are also described using the Gaussian distribution on the free surface as follows:

$$q(r) = \frac{Q}{2\pi\sigma_q^2} \exp\left(-\frac{r^2}{2\sigma_q^2}\right)$$

$$\text{and } J(r) = \frac{I}{2\pi\sigma_j^2} \exp\left(-\frac{r^2}{2\sigma_j^2}\right) \quad (6)$$

where σ_q and σ_j denote distribution parameters of heat flux and current density, respectively. Although the distributions of heat flux and current density may vary

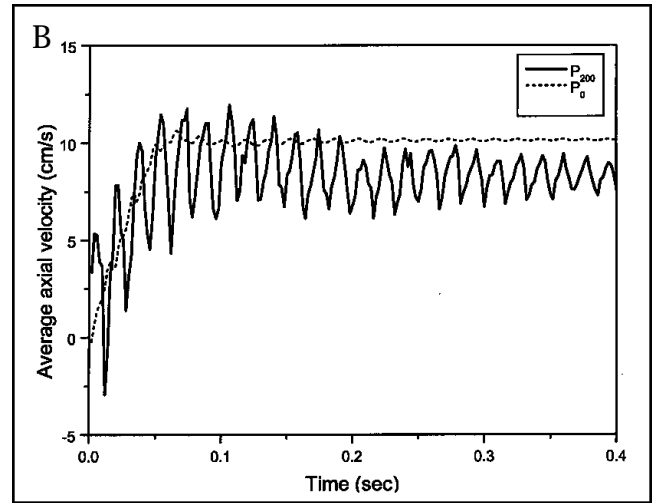
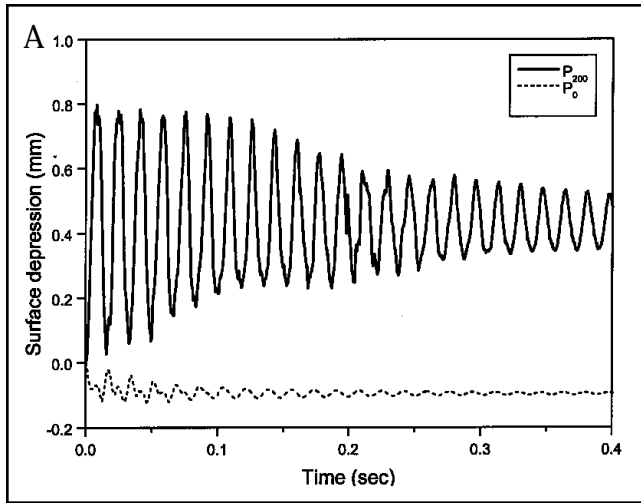


Fig. 5 — Comparison with and without effects of arc pressure ($I = 200$ A, $\gamma = 1200$ dyne/cm). A — Surface depression; B — average axial velocity.

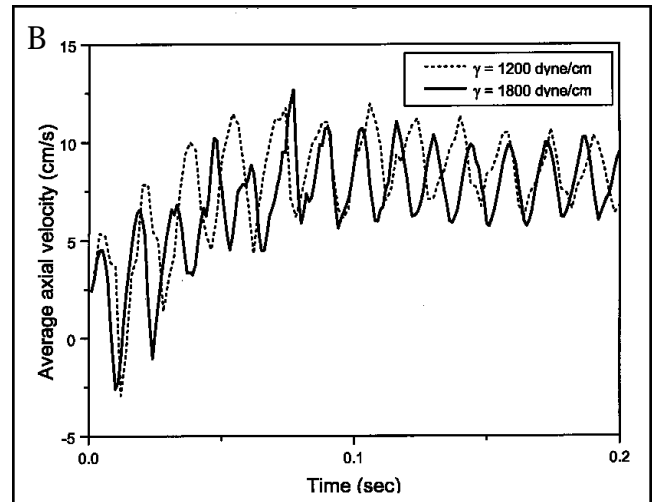
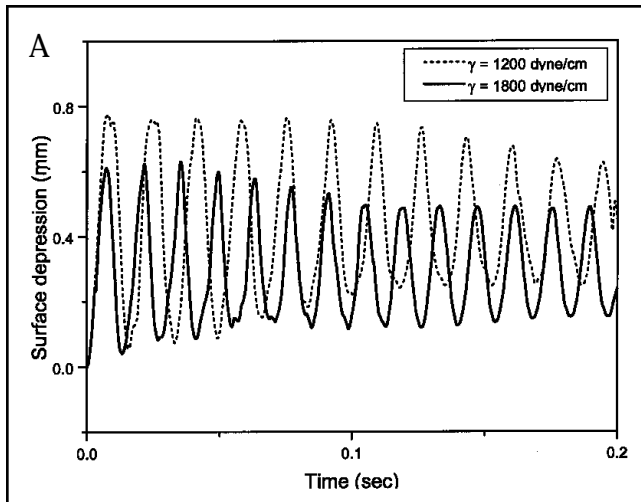


Fig. 6 — Effects of surface tension on surface depression and axial velocity ($P = P_{200}$, $I = 200$ A). A — Surface depression; B — average axial velocity.

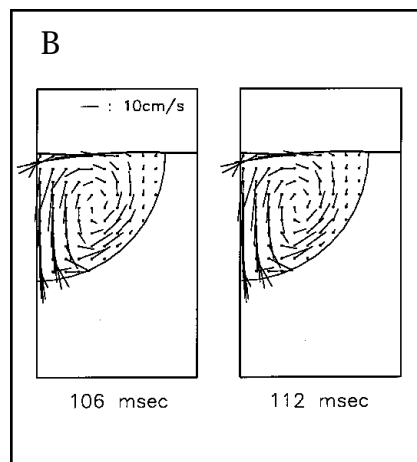
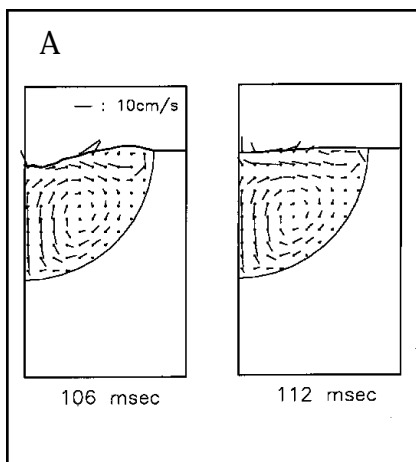


Fig. 7 — Surface profiles and convection patterns due to surface-tension gradient ($P = P_{200}$, $I = 200$ A). A — $d/dT = -0.49$ dyne/cmK; B — $d/dT = 0.49$ dyne/cmK.

tension gradient is ignored. Surface depression decreases with higher surface tension coefficient as in Fig. 6A because higher pressure is required to deform the pool surface of higher surface tension. However, the axial velocity is not affected by the surface tension coefficient as in Fig. 6B.

When the surface-tension gradients of $\pm .49$ dyne/cmK are used with fixed pressure of P_{200} and current of 200 A, the surface profile and flow pattern are illustrated in Fig. 7. In the case of the negative surface-tension gradient, a double loop circulation is calculated as in Fig. 7A. When the surface-tension gradient is changed to the positive value, Marangoni and electromagnetic flow rotate in the same inward direction, which results in faster axial velocity. These flow patterns are similar to those of previous works

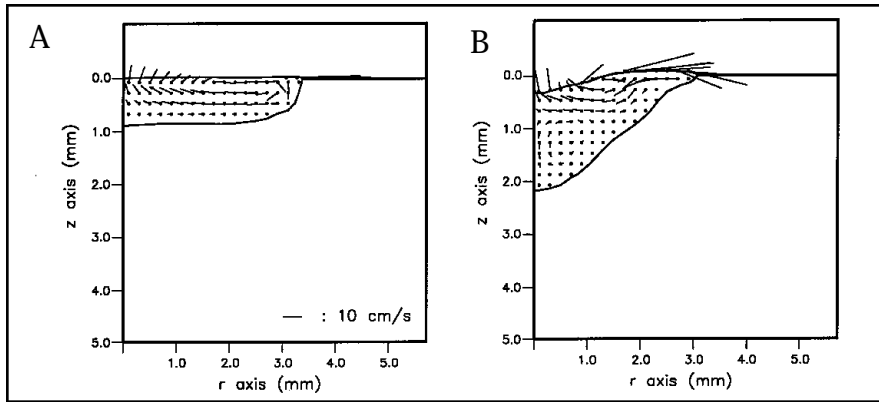


Fig. 11 — Flow pattern and solid-liquid interface for modified arc pressure distributions ($d/dT = -0.49$ dyne/cmK). A — $P = P_{100}^*$; B — $P = P_{200}^*$.

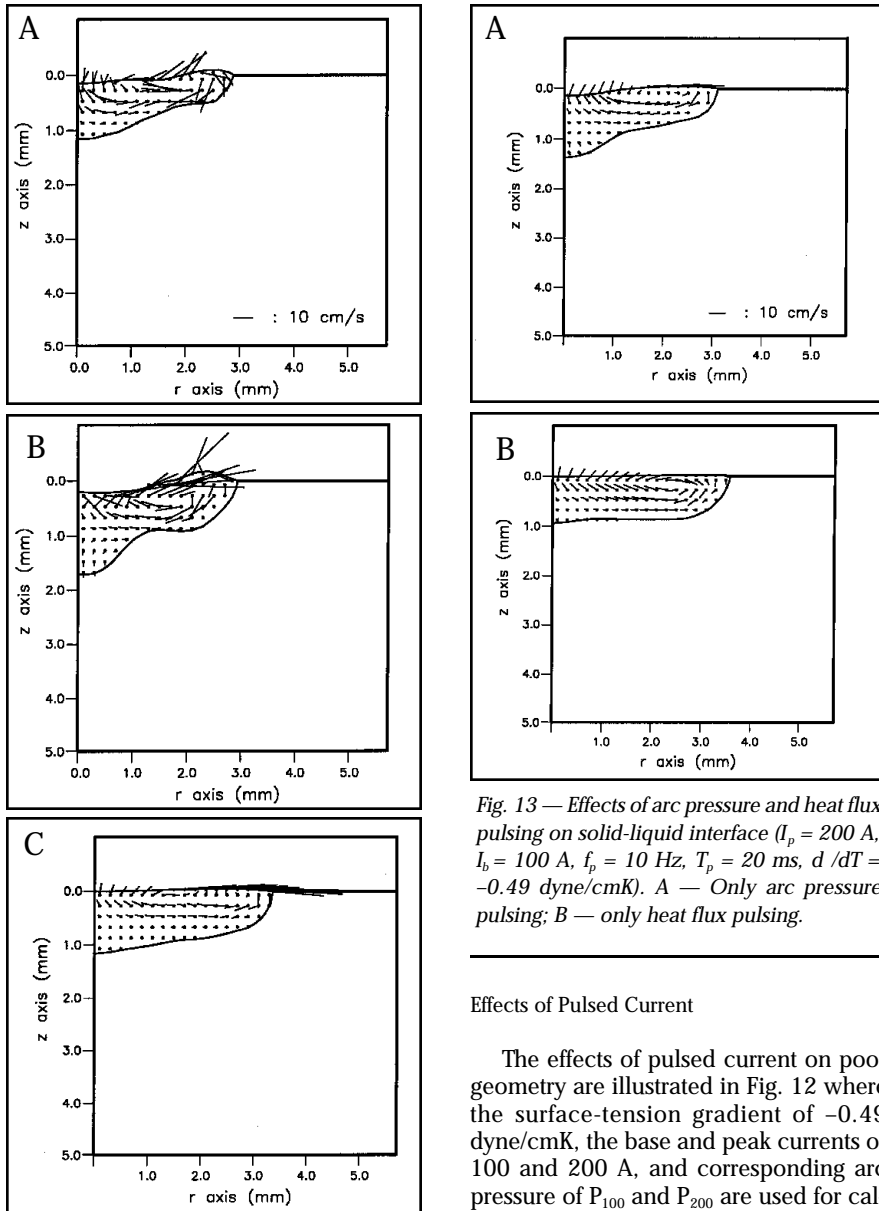


Fig. 12 — Flow pattern and solid-liquid interface for pulse current ($I_p = 200$ A, $I_b = 100$ A, $d/dT = -0.49$ dyne/cmK). A — $f_p = 5$ Hz, $T_p = 10$ ms; B — $f_p = 10$ Hz, $T_p = 20$ ms; C — $f_p = 20$ Hz, $T_p = 10$ ms.

and peak duration increase to 10 Hz and 20 ms (average current of 120 A), penetration in Fig. 12B becomes more pronounced and is almost equal to that of DC 100 A in Fig. 10A. The pool radius and penetration at the outer radius are almost the same as that of DC 100 A so the pool geometry becomes similar to a finger shape. When the peak duration of 10 ms and pulsing frequency of 20 Hz are used (Fig. 12C), penetration does not increase to that in Fig. 12B though the average current of 120 A is the same for both cases. It implies that the peak duration is an important factor in determining penetration, and sufficiently long peak duration is needed to provide enough momentum within the molten pool.

To find out the causes of deep penetration under the current pulsing condition of Fig. 12B, two cases of pulsing of arc pressure and heat flux are simulated as shown in Fig. 13. The condition of pulsing arc pressure and constant heat flux generates deep penetration similar to a finger shape as shown in Fig. 13A. However, another condition of pulsing heat flux and constant arc pressure becomes similar to that of DC 100 A as in Fig. 13B. These results clearly show deep penetration is produced mainly by pulsing of arc pressure at peak duration rather than by pulsing of heat flux.

The relationship between surface depression and penetration is illustrated in Fig. 14 where pulsing frequency and peak time are 10 Hz and 20 ms, respectively. In this case, arc pressures of P_{100}^* and P_{200}^* are used for calculation. A close correlation between surface depression and penetration is observed such that the free surface is depressed just after current pulsing and penetration increases rapidly. After peak current, penetration decreases gradually. Peaks of surface depression and penetration coincide up to 0.5 s, because axial momentum by surface depression is delivered immediately in the small weld pool. When the pool size becomes larger after 0.5 s, there is a time delay between the maximum surface depression and penetration because it takes time to deliver axial momentum and heat by convection in the larger molten pool. The experimental verification and effects of temperature-dependent material properties need to be considered in future work.

Conclusions

Surface depression and pool geometry of DC and pulsed-current arc welding are calculated numerically, and the results lead to the following conclusions:

1) The free surface of a molten pool is depressed mainly by arc pressure, and in-

Effects of Pulsed Current

The effects of pulsed current on pool geometry are illustrated in Fig. 12 where the surface-tension gradient of -0.49 dyne/cmK, the base and peak currents of 100 and 200 A, and corresponding arc pressure of P_{100}^* and P_{200}^* are used for calculation. When the pulsing frequency is 5 Hz and peak duration is 10 ms (average current of 105 A), the penetration in Fig. 12A becomes deeper than that of DC 100 A in Fig. 9A. When the pulsing frequency

