Deformations Arising During Air-Knife Stripping in the Galvanisation of Steel

Graeme C. Hocking, Winston L. Sweatman, Alistair D. Fitt, Chris Breward

Abstract During sheet steel production, the steel surface is usually coated with metal alloy for corrosion protection. This can be done by passing the steel through a bath of the molten metal coating, and controlling thickness with a pair of air knives on either side of the ascending steel strip. Surface quality problems have arisen with recent developments in production. The process was considered at the 2009 Mathematics-and-Statistics-in-Industry Study Group in Wollongong (MISG09) and in subsequent investigations. Previous analyses are extended by the addition of shear terms and by exploring the effect of increased air-jet speeds. A first-order partial differential equation governs the system. This may be used to determine the steady-state coating shape and to study the evolution of any defects that may form.

1 Introduction

In steel sheet production, the steel surface is usually coated with a metal alloy (e.g. zinc/aluminium) to protect against corrosion. In the continuous hot-dipped galvanising process, the steel strip is passed through a bath of molten alloy and then drawn upward until the coating solidifies. Alongside the rising steel strip, a pair of air knives (high velocity air jets) control coating thickness by forcing surplus molten alloy back downwards. New advanced coatings have led to surface quality issues for

Graeme C. Hocking
Murdoch University, Perth, Australia, e-mail: g.hocking@murdoch.edu.au

Winston L. Sweatman
Massey University, Auckland, New Zealand, e-mail: w.sweatman@massey.ac.nz

Alistair D. Fitt
University of Southampton, Southampton, UK, e-mail: a.d.fitt@soton.ac.uk

Chris Breward
University of Oxford, Oxford, UK, e-mail: breward@maths.ox.ac.uk

Bluescope Steel who brought the problem to the MISG 2009 study group. For fixed processing conditions there seems to be a critical air knife pressure below which coating is satisfactory but above which defects may appear. Pocks, the most serious defects, involve substantial local thinning of the coating and a correspondingly severe reduction in corrosion protection. New models [1, 2] improve upon earlier models [3–7] by including air-knife shear. Here, we summarise model development.

2 Modelling the coating process

The development of the mathematical model [1, 2] parallels that of Tuck [3], however, an extra term due to the air-knife shear is included. The model assumes a thin coating and almost-uni-directional flow. The air knife is modelled by a surface pressure distribution and a surface shear stress. The flow is taken as two-dimensional, incompressible, laminar and unsteady, governed by the Navier-Stokes equations:

$$u_t + uu_x + wu_z = -\frac{1}{\rho} p_x + \frac{\mu}{\rho}(u_{xx} + u_{zz}) - g, \tag{1}$$

$$w_t + uw_x + ww_z = -\frac{1}{\rho} p_z + \frac{\mu}{\rho}(w_{xx} + w_{zz}), \tag{2}$$

$$u_x + w_z = 0, \tag{3}$$

where t is time, x and z are respectively the vertical and horizontal coordinates, $\mathbf{q} = (u, w)$ is fluid velocity and p pressure. Subscripts indicate differentiation. Other parameters and typical values are listed in Table 1. Air-knife pressure $p_a(x)$ and

Table 1 Parameters and some typical values

density of the coating	ρ	3×10^3	kg m^{-3}
density of steel	ρ_s	7×10^3	kg m^{-3}
dynamic viscosity of the coating	μ	10^{-3}	kg m^{-1}s^{-1}
gravitational acceleration	g	9.8	m s^{-2}
surface tension coefficient of the coating	γ	10^{-1}	N m^{-1}
scale of thickness of coating	h_0	5×10^{-6}	m
vertical length scale - half-width of air jet	L	5×10^{-3}	m
half-width of the steel strip	d	10^{-3}	m
upward speed of the steel strip	U	2.5	m s^{-1}
maximum centreline speed of the air jet	U_a	30	m s^{-1}
Capillary number (Surface tension)	$\mathrm{Ca} = \mu U/\gamma$	2.5×10^{-2}	
Surface tension quotient	$C = \varepsilon^3/\mathrm{Ca}$	4×10^{-8}	
Reynolds number	$\mathrm{Re} = \rho UL/\mu$	$37,500$	
Stokes number	$S = \rho g h_0^2/\mu U$	0.0003	
Length ratio	$\varepsilon = h_0/L$	10^{-3}	
Pressure scaling	$\mu U/\varepsilon^2 L$	5×10^5	kg m^{-1}s^{-2}
Shear scaling	$\mu U/\varepsilon L$	500	kg m^{-1}s^{-2}

shear stress $\tau_a(x)$ are assumed specified. Coating fluid boundary conditions are

$$u = U, \quad w = 0 \quad \text{at } z = 0 \quad \text{(the substrate)}, \tag{4}$$

$$\mu u_z = \tau_a(x), \;\; p - p_a(x) = -\gamma\kappa, \;\; h_t + u h_x = w \text{ at } z = h(x,t) \;\; \text{(the free surface)}. \tag{5}$$

Curvature $\kappa \approx h_{xx}$ (variation of h with x is small). Set $t = (L/U)\bar{t}$, $x = L\bar{x}$, $z = \varepsilon L\bar{z}$, $u = U\bar{u}$, $w = \varepsilon U\bar{w}$, $p = (\mu U/\varepsilon^2 L)\bar{p}$, $h = \varepsilon L\bar{h}$, $p_a(x) = (\mu U/\varepsilon^2 L)P(x)$ and $\tau_a(x) = (\mu U/\varepsilon L)G(x)$. Drop overbars for convenience. To leading order (1)-(5) become

$$p_x = u_{zz} - S, \quad p_z = 0, \quad u_x + w_z = 0, \tag{6}$$

$$u = 1, \quad w = 0 \quad \text{at } z = 0, \tag{7}$$

$$u_z = G(x), \quad p - P(x) = -Ch_{xx}, \quad h_t + u h_x = w \quad \text{at } z = h, \tag{8}$$

$P(x)$ and $G(x)$ being non-dimensional pressure and shear acting on the coating surface. Based on experimental work [8, 9], realistic functional forms for them are [2]:

$$P(x) = P_{\text{MAX}}(1 + 0.6x^4)^{-3/2}, \tag{9}$$

$$G(x) = \begin{cases} \text{sign}(x) G_{\text{MAX}} \left[\text{erf}(0.41|x|) + 0.54|x| e^{-0.22|x|^3} \right] & \text{if } |x| < 1.73 \\ \text{sign}(x) G_{\text{MAX}} \left[1.115 - 0.24 \log|x| \right] & \text{if } |x| \geq 1.73. \end{cases} \tag{10}$$

Ignoring terms multiplied by $\varepsilon^2 \text{Re} = h_0^2 \rho U/(\mu L) \approx 0.04$ and solving (6)-(8)

$$p = P(x) - Ch_{xx}\,, \qquad u = (S + P'(x) - Ch_{xxx}) \left(\frac{1}{2} z^2 - hz \right) + zG(x) + 1, \tag{11}$$

$$w = \frac{1}{2} z^2 h_x (S + P'(x) - Ch_{xxx}) - (P''(x) - Ch_{xxxx}) \left(\frac{1}{6} z^3 - \frac{1}{2} h z^2 \right) - \frac{1}{2} z^2 G'(x). \tag{12}$$

These values satisfy (6)-(8) except that the last boundary condition becomes a PDE:

$$h_t + \left(h + \frac{1}{2} h^2 G(x) - \frac{1}{3} h^3 (S + P'(x) - Ch_{xxx}) \right)_x = 0. \tag{13}$$

3 Steady-state solutions

Surface tension is neglected as $C \approx 4 \times 10^{-8}$ (also see [5]). Integrating (13) without time dependence gives the coating fluid flux Q. This is identical for all x. So

$$Q = f(h,x) = h + \frac{h^2}{2} G(x) - \frac{h^3}{3} (S + P'(x)), \tag{14}$$

$$\frac{dQ}{dx} = 0 = h'[1 + hG(x) - h^2(S + P'(x))] + \frac{h^2}{2} G'(x) - \frac{h^3}{3} P''(x). \tag{15}$$

Coefficients of the cubic in (14) vary continuously with changes in $G(x)$ and $P(x)$.

Consider the control point (x_c, h_c), where the cubic has a double root. As

$$\frac{\partial f}{\partial h}(h_c, x_c) = 1 + h_c G(x_c) - h_c^2 [S + P'(x_c)] = 0, \tag{16}$$

$$h_c = \frac{1}{2}\left[\frac{G(x_c)}{S + P'(x_c)}\right]\left(1 \pm \sqrt{1 + 4\left[\frac{S + P'(x_c)}{G(x_c)^2}\right]}\right). \tag{17}$$

The negative sign is appropriate. Evaluating (15) at $x = x_c$, using (16), noting $h_c \neq 0$,

$$G'(x_c) = \frac{2}{3} h_c P''(x_c). \tag{18}$$

A simple practical approach to finding the control point is to evaluate h_c at each x using (17) and find the associated flux Q^* with (14). The required x_c and h_c correspond to the minimum Q_c^*.

Using $P_{\mathrm{MAX}} = 0.01$, $G_{\mathrm{MAX}} = 0.1$ in (9) and (10), then $x_c \approx -1.107$, $h_c \approx 6.172$, $Q_c \approx 3.529$ and upstream coating thickness $h_- \approx 43$ and that downstream $h_+ \approx 3.33$.

The final coating thickness decreases as the pressure of the air jet increases. Correspondingly, the thickness of the upstream layer increases as more of the coating alloy drains downwards. Also, as expected, the flux decreases as the coating thickness is reduced.

4 Evolution Of Coating Deformations

Starting with an established coating process in steady state we consider the evolution of a small surface deformation. It is unclear what the origins of such a perturbation might be. In [1], various possibilities are considered including impaction by a particle embedded in the air knife jet. In [2], it is found that a quite large single pressure pulse in the air knife (20%) only creates a small dip, while rapid periodic variations in the pressure (shudder of the air knife) have a minimal effect upon the coating.

Re-writing (13)

$$h_t + c(h,x) h_x = A(h,x), \tag{19}$$

we observe the propagation speed $c(h,x)$ and amplitude $A(h,x)$ of a disturbance are

$$c(h,x) = 1 + G(x)h - h^2(S + P'(x)), \tag{20}$$

$$A(h,x) = h^2(hP''(x)/3 - G'(x)/2). \tag{21}$$

Note that $c(h,x) = 0$ at (x_c, h_c) from (16), and disturbances below the control point propagate downwards towards the bath, while those above propagate upward and are our primary interest.

A comparison of $c(h,x)$ and $A(h,x)$ for a weaker jet and a stronger one [2], verifies results of linear analysis [1, 3]. The term $A(h,x)$ is only significant over a very narrow region close to the control point, whereas the term $c(h,x)$ remains significant well downstream where it approaches $1-h^2S$. Furthermore, for the weaker jet, gravity plays a more significant role as h is larger and $G(x)$ is smaller.

Close to the air knife centre, coating behaviour is directed by the interaction between the shear and pressure terms. Beyond this thin band, $c(h,x) \approx 1+G(x)h-h^2S$ and $A(h,x)$ remains small for all pressures. This suggests that beyond the immediate influence of the jet, perturbations will be marginally stable (neither growing nor decaying) as found in the analysis [3]. There are circumstances where points near the surface travel faster than those near the substrate and others where the reverse is true [1, 2]. In the higher pressure case, the shear term has a greater effect upon $c(h,x)$. If $c(h,x) > 1$ (the high pressure case), then disturbances travel upward faster than the substrate, and depressions break forward (upward). If $c(x,h) < 1$ (lower air-knife pressure) disturbances travel more slowly than the sheet and depressions break backward (downward) into themselves.

Numerical explorations initially used the method of characteristics [1], and later [2] the method of lines (cf. [10]). They confirmed the analysis. In particular, a dip $\delta(x) = -0.3e^{-(x-0.5)^2}$ was added to the steady-state coating thickness and its evolution followed for realistic choices of shear and pressure (9,10), $S = 0.0015$, $G_{\mathrm{MAX}} = 10P_{\mathrm{MAX}}$, and a range of values $P_{\mathrm{MAX}} = 0.0025, 0.005, 0.01$ and 0.05 [2]. At lower values of P_{MAX}, the air knife's influence is very narrow and shear and gravity quickly dominate. The coating surface is slower than the substrate and the dip steepens at the leading edge prior to breaking backwards (downward). At higher values of P_{MAX}, the coating is very thin, and shear terms persist, so that points near the substrate are slower and the back of the dip breaks forwards (upward). For intermediate values of P_{MAX} the depression continues with only minor changes in shape for a long distance upward. After the disturbance passes, the coating near the air knife returns to steady state.

5 Conclusions

The equations derived by Tuck [3] have been modified to include a shear term as in [1], [2]. Results suggest that a disturbance's evolution depends on the air-knife shear $G(x)$ at larger values of pressure $P(x)$, and is dominated by gravity at lower values. Propagation speed depends on the coating thickness. Disturbances of any sort are more persistent for thinner coatings, as then gravity is insufficient to cause a dip to break back into itself and fill the hole. Surface tension and metallurgical effects of solidification may have some effect on these disturbances. However, it would appear unlikely that they will be important with the parameters considered here [2, 5]. There seems no indication that the fluid dynamics undergoes any new calamitous change that might be responsible for the pitting of the surface.

Dimensional values will depend on the actual parameters. For illustration, a final coating thickness of about $15\mu m$ results when using the typical values given here (Table 1) with $P_{\mathrm{MAX}} \approx 0.01$ (associated with air-knife speed $28ms^{-1}$ and steel strip speed 2.5 ms^{-1}) . Increasing the air-knife speed or decreasing the strip speed effectively raises P_{MAX}. In this example, the transition to potential difficulties occurs when the coating thickness drops below $h \approx 1$ (a thickness of about 5 μm) which is associated with $P_{\mathrm{MAX}} \approx 0.05$ or a doubling in air-knife speed combined with slowing of the strip speed. To obtain thinner coats major increases in air-knife speed are needed unless the strip speed is reduced. Slowing the strip speed, although it has the apparent effect of an increase in pressure, allows more time for any disturbances to decay. Application to a real situation depends on the actual values for the other parameters and the numbers here are purely indicative.

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