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AN ANALYSIS OF JET STRIPPING OF MOLTEN METALLIC COATINGS

C.H. ELLEN AND C.V. TU

RESEARCH AND TECHNOLOGY CENTRE

JOHN LYSAGHT (AUST.) LTD. PORT KEMBLA, NSW, 2505 AUSTRALIA

SUMMARY Accurate control of coating thickness in the production of hot dipped steel strip is necessary in order to minimise coating costs, to reduce subsequent strip processing problems and to achieve the anticipated corrosion performance. This paper presents a revised analysis of the jet stripping process, as used to control metallic coating thicknesses, and demonstrates that the inclusion of a surface shear stress term, acting in conjunction with the pressure gradient on the molten metallic film, gives theoretical predictions which closely fit plant collected data. It is argued that pressure gradients effects alone cannot account for the observed results and that the theory without surface shear stresses has obvious defects.

Experimental results are also given indicating strip edge effects. When interaction between opposing jets occurs, the stripping action is shown to be significantly affected and, as a result, the coating thickness along the edges becomes greater than that remote from the edges.

1 INTRODUCTION

The hot dip galvanizing process has long been used for steel sheeting because of the need for corrosion resistant coatings to protect the steel base against adverse environments. Coatings commonly used are based on zinc, aluminium, zinc/aluminium alloys, lead and tin.

Early production of galvanized steel sheets was a batch process involving hand (or mechanically assisted) dipping of precut sheets of steel into a bath of molten metal. A flux was used for surface cleaning and there was virtually no control of coating thickness (Bablik (1950)). This technique was later replaced by a continuous process which involved passing a steel strip continuously through molten metal.

Continuous galvanizing lines commenced operation in 1936 when the basic process, patented by Sendzimir (1938), was applied to strip coating. The same functional sections, described in that patent, are still used in modern continuous galvanizing lines. The main sections of a typical continuous galvanizing line are shown in Figure 1.

The coating section of the hot dip galvanizing line is where the steel strip, after passing through the heat treatment and surface preparation sections, enters a bath of molten metal maintained at a constant temperature. Sink roll and deflector rolls keep the strip submerged and locate the strip pass line. As the steel strip emerges from the bath it carries a surface layer of molten metal with it due to viscous action. The thicknesses of this molten metal film should be controlled effectively if coating metal costs are to be minimised and the final product is to be acceptable.

Coating roll operations were popular between the late 1930's and the 1970's. However, coating rolls place undesirable limitations on coating mass control capabilities. Line speeds must be kept below 60 m/min and there is a tendency for thin strip to break as it passes through the coating rolls. Roll maintenance costs can also be excessively high although the effective life of rolls is to some extent a function of the skill of the line operator.

Because of these limitations, "gas knife" or jet stripping processes were introduced. Jet stripping, which is illustrated in Figure 2, has been used for many years to control liquid coating thicknesses in the paper industry, and its introduction to continuous galvanizing lines has greatly improved the quality of metal coatings on higher speed lines (up to 200 m/min or higher). The coating mass obtained with jet stripping depends mainly on the properties of liquid metal used and other variables such as strip speed, jet plenum pressure, and jet to strip distance. Fluids employed in jet stripping include combusted exhaust gas, steam,

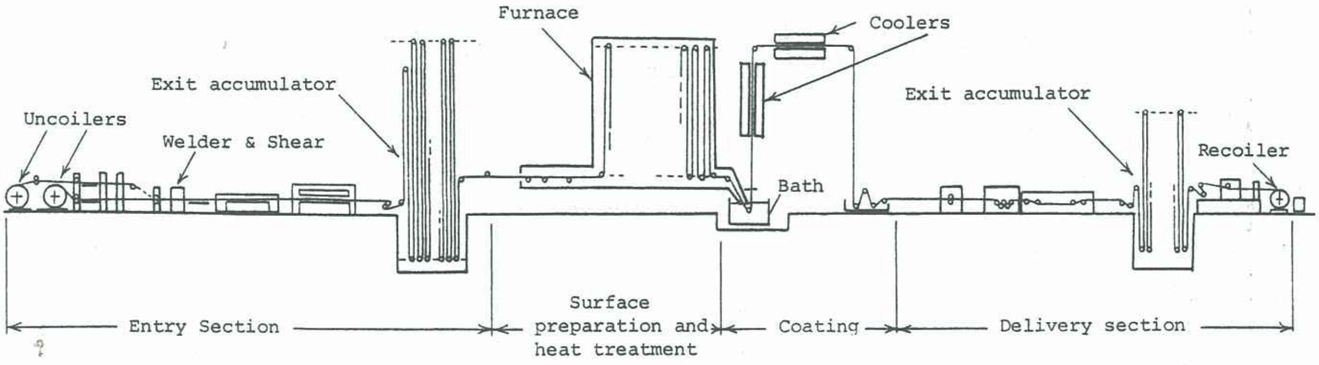

Figure 1 Configuration of typical continuous hot dip galvanizing line

nitrogen and air which, because of its ready availability, is most commonly used.

John Lysaght (Australia) Limited operates five continuous hot dip galvanizing lines all of which control coating mass by air jets. The line speed range of each is governed by furnace and equipment constraints related to the specific line design which, in turn, is based on product processing requirements. In addition, the company has designed and built several mini-galvanizing lines which operate in SE Asia. These lines are also fitted with jet stripping equipment.

The understanding of the process and of the relationship of the process variables is essential for the continued development and improvement of the process, and in the application of coating mass control systems. A theoretical description of the jet stripping process has been given by Reid (1972), and Thornton and Graff (1976). However, because of the lack of reliable data on both jet characteristics and coating mass values, a number of tuning parameters has been used to fit theory and experiment. Many other investigators have explored the process by collecting experimental results and processing conditions from line trials from which regression analysis has given various empirical formulae for prediction of coating masses of liquid metal on a strip (Butler (1970), Harvey & Carlton (1974), Nikoleizig <u>et al</u> (1978), Adaniya & Shoji (1980)).

2 JET STRIPPING THEORY

The problem is defined as steady state vertical withdrawal of a flat plate from a viscous fluid bath. Remote from the meniscus region, a variation of external pressure is imposed (say, by a two-dimensional jet impinging on the moving plate), as illustrated in Figure 2. For a slowly varying film thickness, t (ie $|dt/dx| << 1$), and negligible surface tension, the Navier Stokes equations for a thin film on a plane surface reduce to

$$\mu d^2u/dy^2 - \rho g + dp/dx = 0, \qquad (1)$$

where u is the fluid velocity parallel to the surface (x direction), y is the co-ordinate normal to the surface, ρ and μ are the fluid density and viscosity respectively, g is the acceleration due to gravity and dp/dx is the pressure gradient in the x direction (Figure 2). (In the case of gravity alone $dp/dx = 0$.) Liquid metal films on moving strip solidify far from the bath level and the assumption of constant viscosity in the stripping zone is acceptable since the viscosity of molten zinc or aluminium is insensitive to temperature until the temperature is within approximately 5°C of the freezing point.

The boundary conditions are:

$$u = U \text{ at } y = 0 \text{ (no slip)}$$

and $$\mu du/dy = \tau \text{ at } y = t,$$

where U is the plate velocity, the shear stress, τ, imposed by the external jet gas-fluid interface, is a slowly varying function of x. In all previously published theories of jet stripping the surface shear stress, τ, has been set to zero.

The solution of equation (1), subject to the given boundary conditions, is

$$u/U = 1 - (GT^2/2)(y/t)(2-y/t) + ST\,(y/t) \qquad (2)$$

where T, S and G are the non-dimensional film thickness, shear stress and effective gravitational acceleration defined by

$$T = t(g/\nu U)^{1/2} \quad S = \tau(\mu\rho U g)^{-1/2} \quad G = 1 + (dp/dx)/\rho g.$$

Along the strip, at any position, G and S are known from a knowledge of the jet impingement pressures and the wall shear stresses on the strip. Since the strip speed, U, is much smaller than the air velocity from the nozzle (typically 1% or less), it is unnecessary to correct the shear stress for strip movement.

The non-dimensional withdrawal flux, Q, is given, on integration of equation (2), by

$$Q = T(1-GT^2/3) + ST^2/2, \qquad (3)$$

where $Q = (q/U)(g/\nu U)^{1/2}$ and $q = \int_0^t u\,dy$. The final single-sided coating mass per unit area, M, is given by $M = \rho q/U$.

Under steady state conditions Q must be constant while T changes in response to a changing G and S caused by the stripping jet. Consider the cubic function,

$$f(T) = GT^3/3 - ST^2/2 - T + Q, \qquad (4)$$

which has either two or no positive real zeros (as indicated) in Figure 3). The loci of the zeros, as G and S change, describe the possible variations in coating thickness. It can be seen that the thicknesses will return to their original values unless a bifurcation point, $f'(T)=0$, arises. This bifurcation point describes the only mechanism by which a net thickness change can occur and also defines the maximum flux, Q*, for a given G and S. (The solution which involves an increasing thickness through the jet stripping zone is unacceptable physically and can be shown to be unstable.)

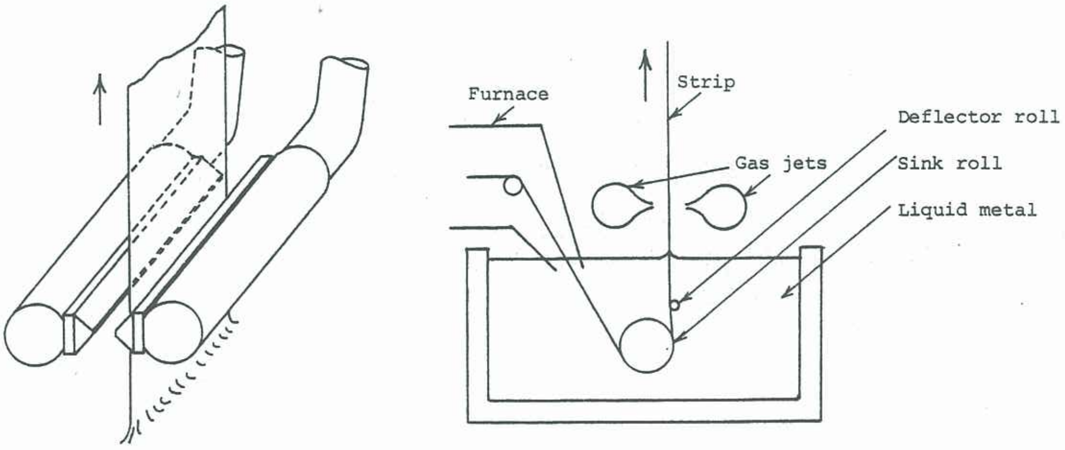

Figure 2 Details of hot dip coating section including jet knives

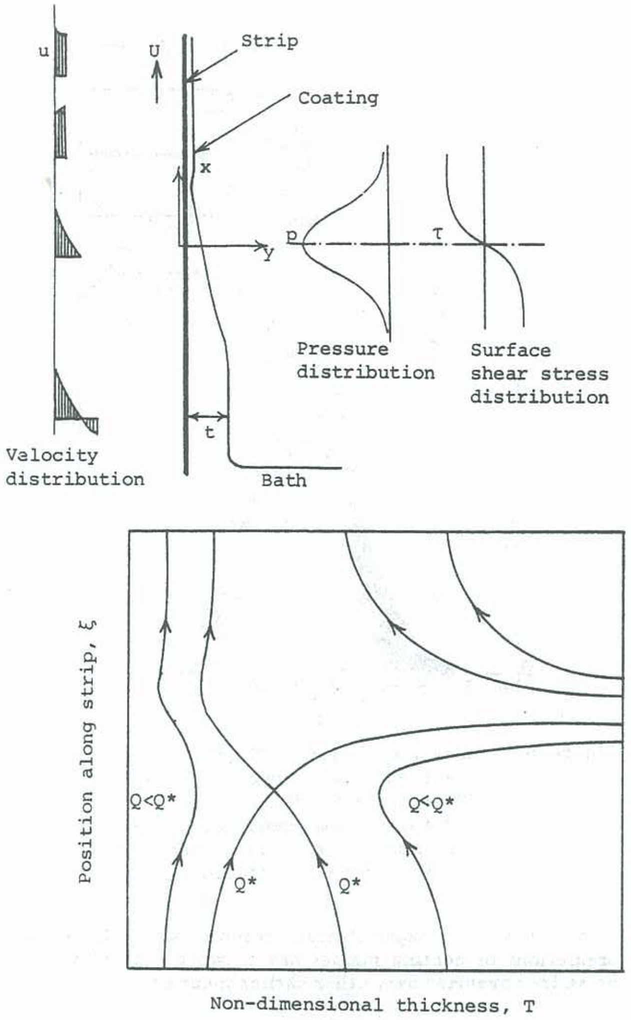

Figure 3 Coating thickness behaviour near the jet stripping zone

Since the stripping action, and solution, depend on the variation of G and S along the strip, it is necessary to have details of them in order to obtain accurate predictions of coating mass.

Flat plate jet impingement has been investigated experimentally using production jets with slot aspect ratios of 1000:1 to 6000:1, plenum pressures in the range 5 kPa to 30 kPa above atmospheric, and jet to plate distances ranging between 8 and 60 times the jet opening. The data may be non-dimensionalised, as suggested by Hrycak (Beltaos (1976)), by plotting p/p_s against $\xi = x/b$, the pressure, p, being non-dimensionalised with the peak pressure, p_s (where x=0), and x=b being the point where $p = p_s/2$. It can be seen in Figure 4, that the experimental results, so plotted, closely fit the curve

$$p/p_s = f(\xi) = e^{-0.693\xi^2}. \tag{5}$$

The agreement is very good in the region where the maximum pressure gradient occurs but there are differences for $|\xi| > 1.6$.

Although no shear stress measurements have been made to date on production jets, the shear stress distributions given by Beltaos (1976) are believed to have sufficient accuracy for calculations of withdrawal flux, ie

$$\tau = -\tau_m \left[\mathrm{erf}(0.833\xi) - 0.2\,\xi f(\xi)\right], \tag{6}$$

where the maximum shear stress, τ_m, is given by Beltaos (1976).

It is of interest to note that the maximum pressure gradient occurs at $\xi = 0.849$, whereas $1.0 < \xi < 1.4$ for the peak stripping condition, as a result of the pressure gradient and the surface shear stress.

3 COMPARISON OF RESULTS

In line trials the strip position, relative to the jets, varies because of the strip shape and other effects. The result is that the strip does not necessarily pass centrally through the jet stripping region. Since the jet to strip distance cannot be measured during trials, the coating masses on each surface of the strip is taken to be half the total coating mass and the jet to strip distances are taken to be half the jet to jet distances. The justification for using this procedure is that small perturbations should be linear and, therefore, when the strip moves closer to one jet and coating mass on that surface decreases, the coating mass on the reverse surface (which has moved away from the opposing jet) increases by the same amount. This characteristic is observed in coating mass measurements taken from the galvanizing lines.

The jet conditions for a number of experimental points were used as data for calculations of coating mass using the theory described in Section 2. A comparison was made by plotting the prediction of coating mass against the measured value for each point, as shown in Figure 5. The comparison between measured values and the zero surface shear theory ($\tau = 0$) has also been made in the figure. Figure 5 shows that the coating mass prediction from the new theory is within 10% of the measured points on average. This should be compared with the average of 60% for points given by the theory with zero surface shear stress in the stripping zone. These results indicate that the new theory, which includes the surface shear stress, gives significantly more accurate predictions of the final coating mass.

It should be noted that Figure 13 in Thornton & Graff (1976), for the limited data given, also appears to show an off-set which is indicative of the need to include the surface shear stress term in the theory of jet stripping.

4 EFFECT OF STRIP EDGES

In continuous galvanizing lines using jet stripping for coating mass control, the jet width must, of necessity, be wider than the strip width. If the coating mass at the strip edge is different from the rest, coiling problems may occur or side trimming may be necessary.

There are three basic factors which have been recognized as playing a role in controlling the coating thickness variation near strip edges. These are: the pick-up of dross floating on the bath surface, the possible three-dimensional effect of

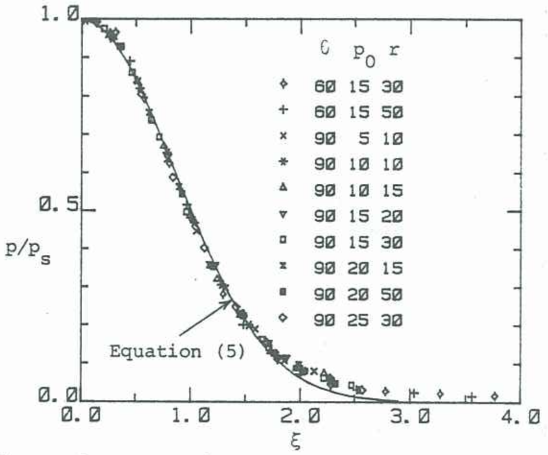

Figure 4 Comparison of non-dimensionalised plate pressure distributions for plane jet impingement (Angle of jet, θ; jet plenum pressure, p_0; maximum impingement pressure, p_s; jet to plate distance/jet opening, r.)

the meniscus at the bath-strip edge, and the interacting stripping jet effects near the edge regions. The latter factor is discussed briefly herein.

In the determination of the impingement pressure distribution near the strip edges, a series of experiments was carried out with single jet and two opposing jet impingement configurations. In order to measure the pressure field near the strip edge, a smooth flat plate, with a series of ten pressure taps near an edge (2.2 mm to 70 mm from it), was moved continuously in the strip direction using a screw of 1.58 mm pitch. At any position, the average pressures at these hole positions were measured using a multiplexer, pressure transducer and a digital voltmeter. Traces of fluctuating pressure components were also recorded on a cathode ray oscilloscope and photographed for later analysis. (Care was taken to ensure that any recorded fluctuations in pressure were not due to structural vibration of the impingement plate.)

For single jet impingement the mean pressure distribution was found not to vary significantly as the edge of the plate was approached. There was, furthermore, no indication of surface pressure fluctuations. The reverse side of the plate was also examined and the surface pressure was found to remain very close to atmospheric.

For opposing jet impingement a significant reduction in the mean pressure distribution was observed near the edge of the plate. This is shown in Figure 6. Towards the edge of the plate, there was a significant reduction in the mean peak pressure, and also in the mean maximum pressure gradient. The recorded pressure fluctuations were also high near the plate edges, as shown in Figure 6. For this set of conditions the fluctuating pressure components occurred at approximately 100-140 Hz (ie with a period of 7 to 10 ms) superimposed on a signal of much smaller amplitude of 500 Hz (2 ms period).

Fluctuating pressures and shear stresses may have serious effects on final coating mass. Consider a fluid element moving with the strip through the stripping region in which, under typical stripping conditions, it will spend 1 to 4 ms. If the period of the pressure fluctuations are of the same order, uneven edge stripping can be expected to occur.

Several existing devices or jet configurations are used in production in order to prevent or reduce, to some extent, the interaction of opposing jets. Work is continuing on improving edge control.

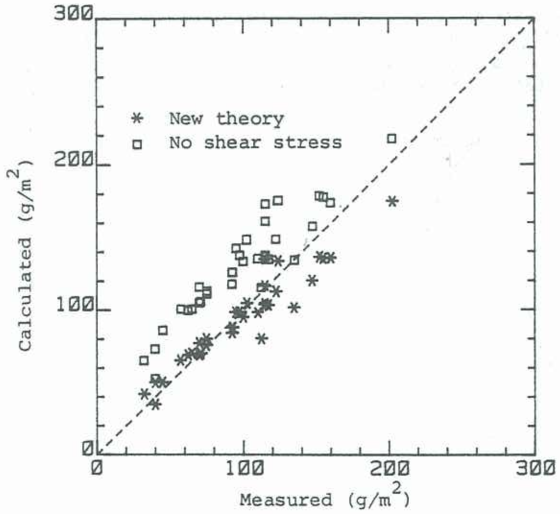

Figure 5 Comparison of theoretical and experimental coating masses

5 SUMMARY AND CONCLUSIONS

An analysis of the jet stripping process with the surface shear stress term included has been presented. A comparison of experimental results with theoretical predictions of coating masses has shown the new theory to be an improvement over other earlier theories.

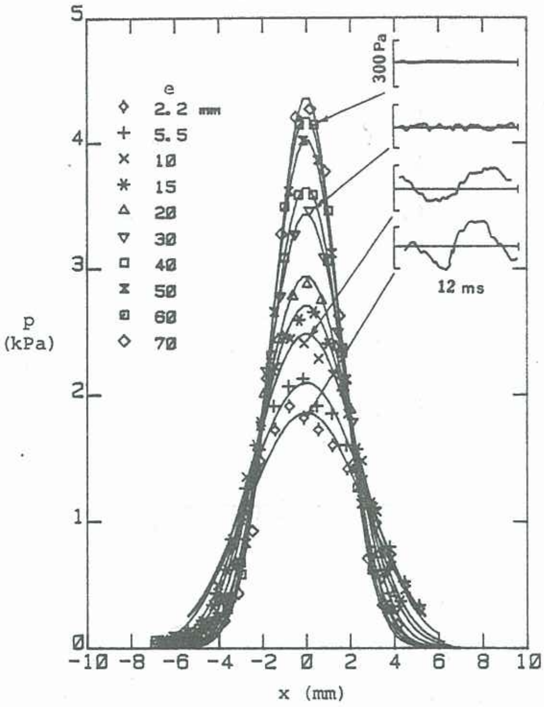

Figure 6 Measured pressure distributions near a plate edge with opposing jets in operation (Distance from plate edge, e; jet opening, 0.9 mm; plenum pressure, 5kPa; jet to jet distance, 19 mm; measurement plate 5mm thick, centrally located.)

Impingement pressure fields, including surface pressure fluctuations caused by opposing jets near the edge of a flat plate, are seen to be significant in influencing coating build-up near strip edges.

6 ACKNOWLEDGEMENT

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