Minimizing air entrainment

(in a shot sleeve during slow shot stage)

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INTRODUCTION

The speed of the plunger in a horizontal shot sleeve must be carefully controlled to avoid unnecessary entrainment of air in the metal and at the same time minimize heat losses in the sleeve. If the plunger moves too fast, large waves are created on the surface of the liquid metal that may overturn and entrain air into the metal, which will then be carried into the die cavity. A plunger moving too slowly results in waves reflecting from the opposite end of the shot sleeve. The reflected waves prevent proper expulsion of air into the die cavity. In either case, the outcome is excessive porosity in the final casting.

In this article a general solution is derived for the plunger speed as a function of time that allows the engineers to precisely control the behavior of metal in the shot sleeve during the slow shot stage of the high pressure filling process, minimizing the risk of air entrainment.

MATHEMATICAL MODEL

The dynamics of waves in a horizontal shot sleeve can be analyzed by drawing an analogy with flow in an open channel. For a shallow wave travelling along the free surface due to gravity g, the speed of the wave, c_0, is given by

$$c_0 = \sqrt{gh_0} \qquad (1)$$

Note that the wave speed is independent of the properies of the metal.

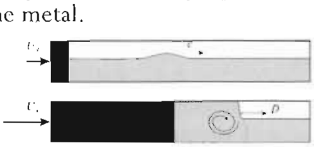


Figure 1. Schematic illustration of the propagating surface wave when the plunger is moving slowly (top) and the hydraulic jump forming ahead of fast moving plunger

As the plunger accelerates, it first catches up, then overtakes the waves created by it during the slow stage. As a result, metal piles up to the top of the sleeve in front of the plunger, creating a flow condition called hydraulic jump at which the flow undergoes a sharp transition from a relatively slow and laminar regime downstream to a fast and turbulent one behind the jump (Fig. 1). The speed of this front, D, can be estimated from the balance of mass as

$$D = \frac{U_p}{1-\varepsilon} \qquad (2)$$

where Up is the plunger velocity and ε is the fill fraction of the sleeve ahead of the front [Garber, 1982]. Equation (2) shows that the hydraulic jump always moves faster than the plunger and that its speed is also independent of the metal properties.

A more detailed analysis is possible by modeling the flow of metal in a rectangular shot sleeve of length L and height H using the shallow water approximation [Lopes *et al*, 2000]. The flow is modeled in two dimensions, with the x axis directed along the direction of motion of the plunger, and the z axis pointing upwards. If viscous forces are omitted, then the flow has only one velocity component, u, along the length of the channel. Pressure at every point in the flow is then hydrostatic

$$P = P_0 + \rho g(h-z) \quad (3)$$

where $h(x,t)$ is the height of the fluid at point x and time t, as shown in Figure 2.

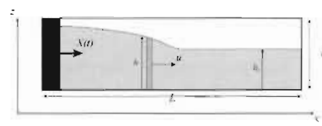


Figure 2. Schematic representation of the flow in a shot sleeve and the coordinate system

The plunger speed in the positive x direction is given by $dX/dt=X'(t)$, where $X(t)$ defines the position of the plunger at time $t>0$ at the moving surface of the plunger. As the plunger moves along the length of the channel it sends waves traveling forward along the metal surface. Each wave is associated with a small segment of the metal free surface and the column of metal directly below it (Fig. 2). The location, metal speed and depth in a wave that separates from the surface of the plunger at time $t=tp$ are given by [Lopes *et al*, 2000]:

$$x(t) = X(t_p) + \left(c_0 + \frac{3}{2}X'(t_p)\right)\cdot(t-t_p)$$
$$u(x,t) = X'(t_p) \qquad (4)$$
$$h(x,t) = \frac{1}{g}\left(\sqrt{gh_0} + \frac{1}{2}X'(t_p)\right)^2$$

PLUNGER ACCELERATION

According to Eq. (4), the metal speed, u, and depth, h, in each wave are constant and depend only on the time of the wave separation from the plunger, tp. They both increase with the speed of the plunger X'. Therefore, the first conclusion is that to maintain a monotonic slope of the metal surface in the direction away from the plunger, the latter *must not decelerate*, that is:

$$X''(t) \geq 0 \qquad (5)$$

If this condition is not satisfied, then there will be waves sloped in both directions, as shown in Fig. 1. When they reflect off the end of the sleeve and travel back towards the plunger, it creates unfavorable conditions for the evacuation of air from the sleeve and into the die cavity.

CONTROLLING THE WAVES

Once a wave detaches from the plunger at time $t=tp$, it travels at a constant speed given by

$$u + c = X'(t_p) + \sqrt{gh} = \sqrt{gh_0} + \frac{3}{2}X'(t_p) \qquad (6)$$

According to Eq. (6), when the plunger is accelerating, then each successive wave moves faster than the waves generated earlier. This will lead to a steepening of the surface slope as the waves travel further down the channel, and can potentialy result in overturning.

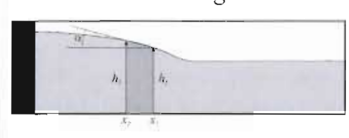


Figure 3. The illustration for calculation of the slope of the metal's free surface

The wave slope, defined in Fig. 3, is a function of the plunger speed at the time of the wave creation, $t=tp$, and at time t is [Reikher and Barkhudarov, 2008]:

$$\tan(\alpha) = \frac{1}{g}\cdot\frac{\left(c_0 + \frac{1}{2}X'(t_p)\right)\cdot X''(t_p)}{c_0 + \frac{1}{2}X'(t_p) - \frac{3}{2}X''(t_p)\cdot(t-t_p)} \qquad (7)$$

Figure 5

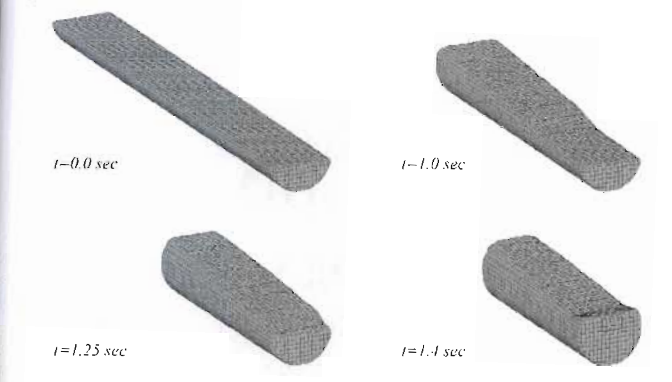
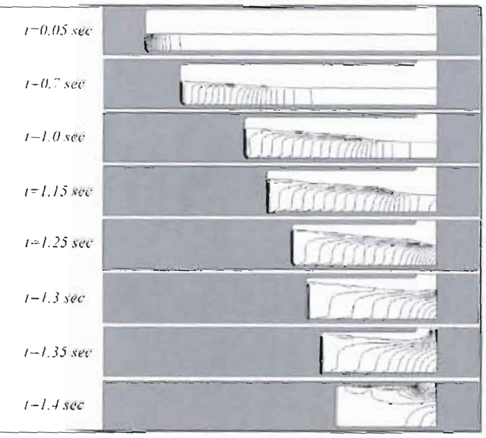


Figure 6



Interestingly, if the plunger moves at a constant speed, i.e. $X''(tp)=0$, then the right-hand side of Eq. (7) becomes zero and the slope of the free surface is horizontal.

If the plunger accelerates, then the denominator on the right-hand side of Eq. (7) decreases and the slope increases with time. When the denominator reaches zero, the slope becomes vertical. The maximum slope in a wave, αmax, is achieved when the wave reaches the end of the shot sleeve at $t=tL$. This time can be computed from the constant wave speed and the distance it has to travel from the point of its creation at the plunger surface to the end of the sleeve at $x=L$:

$$t_L = t_p + \frac{L - X(t_p)}{c_0 + \frac{3}{2}X'(t_p)} \quad (8)$$

Replacing t in Eq. (7) with tL and rearranging terms yields an equation for the plunger acceleration as a function of the maximum wave slope αmax along the length of the shot sleeve:

$$X''_{\alpha_{max}}(t_p) = \frac{\left(c_0 + \frac{1}{2}X'(t_p)\right)\cdot\left(c_0 + \frac{3}{2}X'(t_p)\right)\cdot\tan(\alpha_{max})}{\frac{1}{g}\left(c_0 + \frac{1}{2}X'(t_p)\right)\left(c_0 + \frac{3}{2}X'(t_p)\right) + \tan(\alpha_{max})\cdot\left(L - X(t_p)\right)} \quad (9)$$

Equation (9) can now be used to calculate the velocity of the plunger as a function of time that maintains a *certain* slope of the metal surface during the slow shot stage. For example, if αmax is set equal to 10 degrees, then the plunger movement given by Eq. (9) ensures that the slope of 10 degrees is not exceeded *anywhere* and *anytime* during the motion of the plunger. Note that the plunger velocity given by Eq. (9) is only a function of the initial amount of metal, $h0$, and the length of the sleeve, L, and not of the metal properties.

Equation (9) can be used to obtain the slope αmin of the metal surface right at the plunger by setting $t=tp$:

$$\tan(\alpha_{min}) = \frac{X''(t_p)}{g} \quad (10)$$

Equation (10) gives the *initial* surface slope for a wave detaching from the plunger at time $t=tp$; it is a function of only the plunger's acceleration and not its position or even velocity. As the wave propagates along the length of the channel it steepens reaching the maximum slope, αmax, at the end of the channel at $x=L$, given by Eq. (9).

Equations (5) and (9) give the range of acceptable values for the plunger acceleration during the slow shot stage

$$0 \le X''(t) \le X''_{\alpha_{max}}(t) \quad (11)$$

Two things are achieved when the plunger acceleration stays within this range. Firstly, the slope of the metal surface is directed away from the plunger and towards the opposite end of the shot cylinder, helping to direct the air from the sleeve and into the runner system. Secondly, the slope will not exceed the angle defined by αmax at any time during the slow shot process, preventing wave overturning and the entrainment of air in the metal.

RESULTS

Figure 4 shows numerical solutions of Eq. (9) for the plunger position, $X(t)$, acceleration, $X''(t)$, and speed $X'(t)$ (the latter is shown as a function of both time and distance along the channel length) for several values of αmax. The integration was done for a shot cylinder of length $L=0.7$ *m* and height of $H=0.1$ *m* and the initial fill fraction of 40%, i.e., $h0=0.04$ *m*.

As expected, the plunger motion is slower for smaller values of αmax. It takes the plunger 1.66 seconds to get to the end of the shot sleeve for the most conservative case considered with $\alpha max=5o$, while for $\alpha max=90^{\circ}$ the time is 0.83 seconds. However, these times will be longer if there is an additional constraint of the plunger velocity not to exceed the critical velocity at which the metal surface reaches the ceiling of the channel at $h=H$ [Garber, 1982]:

$$X'_{cr} = 2\left(\sqrt{gH} - \sqrt{gh_0}\right) \quad (12)$$

and is shown in Fig. 4 by the horizontal dashed line. For the selected parameters of the shot sleeve $X'cr=0.73$ *m/sec*. Even for $\alpha max=5^{\circ}$ the plunger velocity reaches the critical value after it moved just over 60% of the channel length, at $tc=1.35$ sec. For steeper surface slopes the critical velocity is reached at earlier times, for example, for $\alpha max=90^{\circ}$ $tc=0.58$ sec and the plunger position is 22% of L.

When the plunger reaches the critical velocity, the metal surface comes in contact with the ceiling of the shot cylinder. Beyond this point the shallow water theory used here becomes invalid. It can also be argued that if the plunger continues to accelerate, then the potential for creating an overturning wave increases since all the energy of the flow is now redirected forward by the walls and ceiling of the channel. It is usually recommended to limit the plunger velocity to the critical value during the slow shot stage.

Figure 4