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The Analysis of Molten Metal Flow in the Hot Chamber Pressure Die Casting Process

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SUMMARY The basic features of the hot chamber process for casting zinc alloy are described. The metal pressure produced by the hydraulic injection system falls off with increasing speed, while the pressure requirement for the metal feed system increases with speed. A graphical method is used to illustrate the equilibrium of the process, and the effect of changing variables. The pressure losses of the gooseneck, nozzle and die are analysed theoretically and experimentally, with good agreement being obtained. Considerable improvements have been made in the hydraulic aspects of machine and die design, but further advances are possible and desirable.

1 INTRODUCTION

The process is used for the volume production of components, often of complex shape, with a minimum of machining or other secondary operations. The material cast is usually zinc alloy No. 3 and therefore the paper is confined to calculations for this metal, though much of the theory is of general application to molten metals. The process has been operated successfully for many years, in spite of poor hydraulic design of machines and poor design of the molten metal flow systems used to make the castings. In recent years research into pressure die casting has shown that large reductions in production cost are possible, combined with better and more consistent quality of the products (1, 2 & 3). This paper describes some investigations into problems of fluid flow during the period of metal injection.

2 DESCRIPTION OF THE HOT CHAMBER PROCESS

The main features are as follows:

(a) A plunger pump having a vertical axis is immersed in a bath of molten metal (Fig. 1 reproduced from (1)) and is driven by a hydraulic or pneumatic ram. The name of the process is derived from the placement of the pump in the molten metal. This is not possible with some metals, e.g. aluminium alloys and an alternative process referred to as "cold chamber" is used in such cases.

(b) The cavity is formed between two dies, one mounted on the fixed platen of the machine, and the other on the moveable platen (Fig.1). The finished casting is ejected by retraction of the moveable die and the subsequent operation of ejector pins mounted in this die.

(c) The pump chamber, usually referred to as the shot sleeve is connected to the die by means of a channel referred to as the gooseneck and a self aligning tubular member called the nozzle. The nozzle is maintained at a high enough temperature to prevent freezing of molten metal in this component.

(d) From the nozzle, metal passes through the fixed die half which incorporates a water cooled member called the sprue pin. Metal is solidified here after cavity fill, and surplus molten material gravitates back to the molten metal pot.

(e) From the sprue area, metal is delivered to runners and gates, which control the flow of metal into various parts of a cavity, or proportion the flow between several different die cavities.

(f) The energy required to make a casting is derived from a hydraulic accumulator charged with nitrogen gas. Oil is pumped into the accumulator during idle periods in the casting cycle. When the dies close, metal injection is initiated, usually by a slow (circa 0.2 m s^{-1}) movement of the injection plunger driven from pump power.

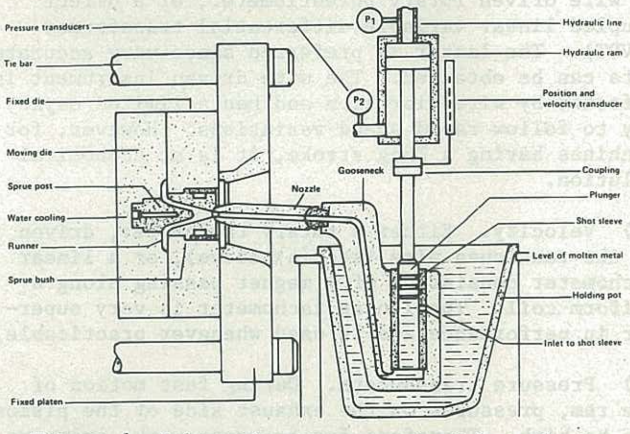

Figure 1 Schematic arrangement of hot chamber pressure diecasting process

During this period, metal is moving into the nozzle, and air is escaping through vents in the dies. A fast acting valve (referred to as the shot valve) then connects the accumulator to the injection ram and metal is injected at high velocity into the die cavities. The cavity fill time is usually in the range of 0.01 s to 0.1 s and volume flow rates are of order 1 to 20 x 10^{-3} m^3 s^{-1}.

Modern casting designs require gate velocity into the die to be in the range 30 - 50 m s^{-1}. These requirements arise from rapid heat transfer rates in the die and the nature of metal flow from the gate and through the cavity. They result in a requirement for rapid acceleration of the metal to attain a Reynolds Number in the range of 10^4 to 10^6. The kinetic energy of the flowing metal is considerable, and must be supplied during a time interval of a few milliseconds. This kinetic energy must also be dissipated during the plunger deceleration phase at the end of the shot.

As a result of these difficult and often conflicting requirements, the design of the machine components is a compromise. Large losses of energy can occur in the hydraulic system of the machine and in the metal transfer system during the injection phase. These losses have been studied in an attempt to improve the process.

3 EXPERIMENTAL WORK ON HOT CHAMBER MACHINES

Measurements are required during the short period when the plunger is displacing metal through the gooseneck, nozzle, sprue, and runners, into the die cavity. From these measurements, both the hydraulic performance of the machine and the pressure losses in the metal flow system can be derived.

The basic variables to be measured are the speed of the plunger and the force exerted on the molten metal. The metal pressure in the shot sleeve can be calculated. It would be desirable to measure metal pressure directly at a number of places, but this is not possible with simple portable instrumentation as used in plant trials.

The pressure and velocity must be related to the position of the metal front at any time and therefore a plunger displacement transducer is also required. The position of transducers is shown in Fig. 1.

3.1 Pressure, Velocity and Displacement Transducers

In the current work, the instruments were:

(a) Plunger displacement. Either a spring tensioned wire driven rotary potentiometer, or a direct coupled linear variable differential transformer (LVDT). The latter is preferred since very accurate data can be obtained. The wire driven instrument is affected by wire vibration and has a limited capacity to follow rapid speed variations. However, for machines having a long stroke, it is an economical solution.

(b) Velocity. Either a rotary tachometer, driven by the tensioned wire (see (a) above), or a linear tachometer consisting of a magnet passing along a uniform coil. The linear tachometer is very superior in performance and is used whenever practicable.

(c) Pressure transducers. During fast motion of the ram, pressures on the exhaust side of the piston can be high. Therefore for accurate work, pressure transducers are mounted on both inlet and exhaust lines, or preferably on the hydraulic cylinder itself. Most of the current work involved the use of semi-conductor strain gauge instruments, but some failures were experienced, due to pressure shock in the hydraulic lines. Additional transducers are now being evaluated, including both bonded and unbonded strain gauge types. Damping orifices are also being used, designed to derate the dynamic response of the pressure transducers to that of the galvonometer pens of the U.V. recorder. These pens have a natural frequency of 2500 Hz, chosen to have an adequate response for die casting research.

3.2 Signal Conditioning, Computing and Recording.

Each of the transducers requires power supplies and signal conditioning equipment to produce stable signals at the power level required for input to the galvanometers of a U.V. recorder. In the equipment developed by CSIRO, continuous computing is also carried out (4). The effective oil hydraulic pressure is calculated, allowance being made for the difference in effective area of the two sides of the ram. In addition, the coefficient of discharge of the flow system is continuously calculated from the transducer signals, using information about metal density, area of hydraulic ram, area of the plunger and area of the casting gate, set as voltages by precision potentiometers.

A typical U.V. trace of pressure, velocity and displacement is shown in Fig. 2, and the displacement trace can be correlated with the position of the metal front in a system such as that of Fig. 1. It can be seen that the timing of events in the die-casting process is well suited to a U.V. recording technique at paper speeds of order 0.2 - 1 m s^{-1}. From traces such as that of Fig. 2, the metal pressure and velocity at the plunger can be derived at particular stages of the injection process, e.g. when the metal is emerging from the nozzle or when the metal is flowing through the gate into the die cavity.

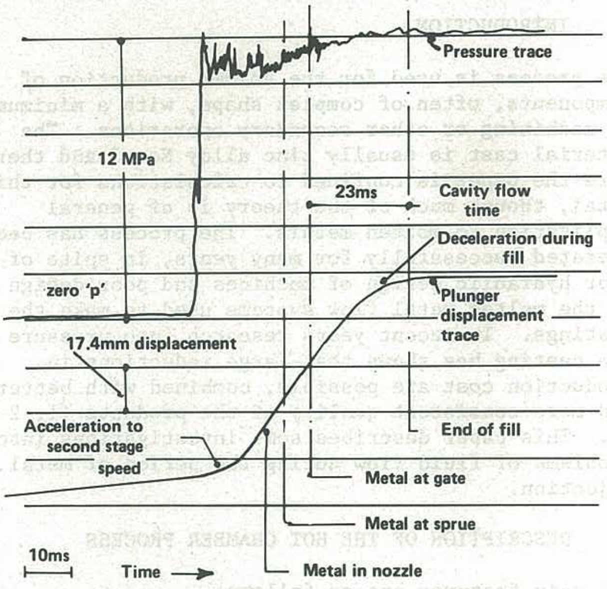

Figure 2 Typical U.V. trace

3.3 The Planning of Production Trials

Before taking instrumentation to a die casting plant, tapping and fixing points for transducers have to be arranged, and calibrations checked. In addition, accurate information is needed concerning the dimensions of gooseneck, nozzle and plunger. If possible, tests are organized to coincide with production on dies likely to yield additional information to assist in future die design. Such dies could incorporate new ideas in feed system design, where information is needed on pressure losses due to metal flow. Gate areas, runner areas, casting volume and other relevant data are collected before the trial, so that features of the U.V. traces, such as the arrival of metal at the gate, can be immediately identified and analysed. This is essential, as confusing results are often obtained in trials, due to freezing problems, machine malfunction, etc.

4 THE HYDRAULIC PERFORMANCE OF THE INJECTION END

Die casting machines are specified in terms of the locking force available to clamp the dies, and the static injection force available to actuate the plunger and pass metal into the die cavity. Knowing the area of the plunger, the static pressure on the metal can be calculated, and from this, the locking force needed for a certain die can be estimated. However, during metal injection, the hydraulic ram is moving at speeds of order 1 - 3 m s^{-1}, and flow in the valves and pipes is turbulent (8). Pressure losses are large, and in general are proportional to the square of ram speed. At a certain speed the pressure is dissipated as hydraulic losses and this speed is referred to as the dry shot speed. If the plunger velocity (or metal flow rate) is plotted on a square scale, against a linear pressure scale, the available pressure for any flow rate is a straight line and is known as the machine characteristic (Fig. 3). The slope of this line is a function of the flow coefficient of the hydraulic lines as discussed in a previous paper (5). If the system pressure is changed the characteristic moves to a

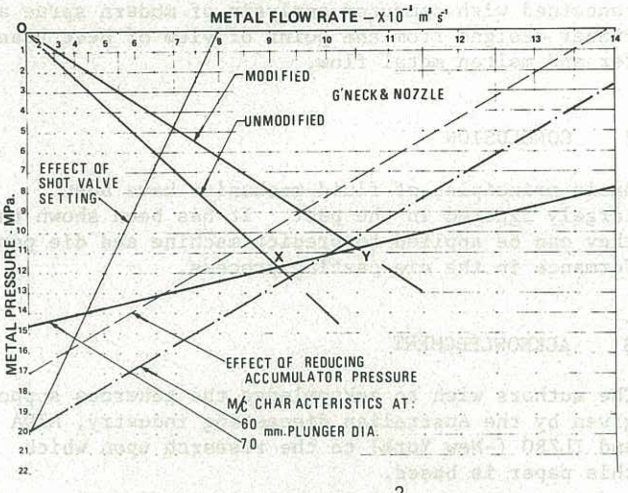

Figure 3 Typical p-Q^2 diagram

parallel position (no change in flow coefficient). If flow is throttled by a speed control valve, the dry shot speed is reduced, and the slope of the characteristic changed (Fig. 3). Both methods can be used for process control. Changing the system pressure involves altering the volume of nitrogen gas in the accumulator, but minimises pressure and die flashing. Throttling the flow of oil is the common method of control, and throttling valves are generally of poor design, as well as being uncalibrated, particularly in older machines.

Modern machine designs have high dry shot speeds (> 5 m s^{-1}), but most old equipment is severely limited by poor design of the hydraulic circuits which results in unnecessary pressure losses and excessive inertia effects in the hydraulic lines. The trace of Fig. 2 refers to a modern machine, but pressure traces from older machines show large pulsations due to inertia effects. These are generally undesirable, as they cause excessive metal pressure and die flashing at the end of cavity fill. The requirement for locking force is doubled in many practical cases, thus increasing costs.

5 THE DESIGN OF GOOSENECK AND NOZZLE

Early designs of gooseneck (Fig. 1) were made by casting around sand cores, and geometry was often good from the point of view of smooth metal flow. Flow rates were moderate and the hydraulic power of the machine was low. Modern machines often incorporate machined goosenecks with the passages produced by drilling (Fig. 4(a)). However, the trend is to thinner castings requiring fast fill rates and high gate velocity (of order 40 m s^{-1}). Metal velocity can be very high in the gooseneck and nozzle, resulting in large pressure losses at bends, inlets and at changes of cross section. The analysis of pressure requirements for the designs of Fig. 4(a) and (b) is discussed below, and compared with experimental measurements.

5.1 Theoretical Flow Analysis

The analysis assumes that:

- the molten metal is completely liquid and is Newtonian;
- the flow is steady and predominantly one dimensional along the axis of the channel;
- the variation of viscosity and density with temperature is negligible;
- the air pressure built up in the die cavity is negligible.

With these assumptions Bernoulli's equation can be applied to the metal flow between the plunger and the nozzle exit and the following equation can be derived:

$$p_1 = \frac{\rho u_2^2}{2} - \frac{\rho u_1^2}{2} + \Delta P \text{ losses} \qquad (1)$$

where p_1 = metal pressure at the plunger
u_2 and u_1 = metal velocity at the nozzle exit and the plunger respectively
ρ = density of molten metal = 6.12 for molten zinc at 400°C (6)
ΔP losses = total pressure losses between positions 1 and 2

The first and second terms in the R.H.S. of equation (1) represents the pressure equivalent of the kinetic energy requirement. The third term represents the sum of the pressure losses due to flow through the bends, entry change of cross-sectional area and the straight sections of the channels. In calculating these pressure loss components standard formulae and pressure loss coefficients (K) are used (Ref. 8). The effect of surface roughness on the pressure losses is also taken into account.

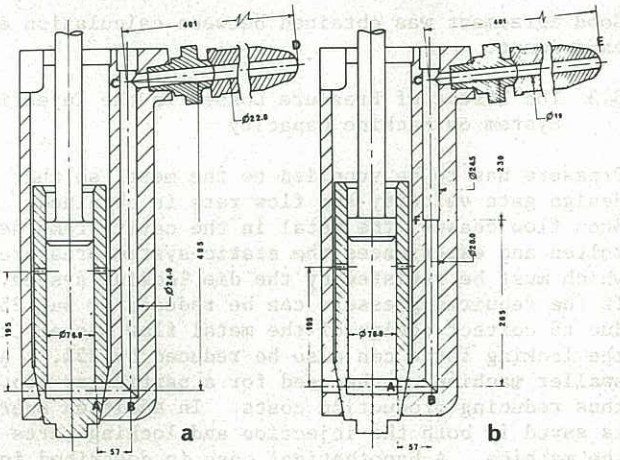

Figure 4 Gooseneck designs (a) Mod. (b) Unmod. (dimensions in mm)

TABLE I
CALCULATED PRESSURE AT 4.8 x $10^{-3} m^3 s^{-1}$

	Unmod. g'neck (Fig. 4b) MPa	Mod. g'neck (Fig. 4a) MPa
Entry A	0.36	0.17
Bend loss (B & C)	1.45	0.86
Enlargement loss	0.08	Nil
Straight section loss	0.80	0.40
Total pressure loss	2.69	1.43
K.E. (nozzle exit)	0.88	0.49
Total pressure	3.57	1.92

TABLE II
PERCENTAGE KINETIC ENERGY INCREASE ON MOLTEN METAL DUE TO MODIFICATIONS IN THE GOOSENECK
(Nozzle diameter = 20 mm)

Plunger dia.	UNMODIFIED GOOSENECK			MODIFIED GOOSENECK			% Increase in kinetic energy
	Max. flow rate	Velocity at nozzle exit	Kinetic energy	Max. flow rate	Velocity at nozzle exit	Kinetic energy	
(mm)	$x\ 10^{-3}m^3s^{-1}$	$m\ s^{-1}$	Joule s^{-1}	$x\ 10^{-3}m^3s^{-1}$	m^{-1}	Joule s^{-1}	
70	9.15	29.13	23,827	10.50	33.42	35,989	51.0
60	9.35	29.76	25,412	10.36	32.98	34,580	36.0

The result of the calculation of the pressure losses is shown in Table I. This shows that significant pressure loss can occur, especially in the bends and entry. Therefore, some modifications were done (Fig. 4(a)). These involved enlargement of the channel, in order to reduce the metal velocity in these channels. The main limitation on increasing the size of the channel is that more air has to be displaced during injection. Furthermore, it is also desirable to have metal velocity in the nozzle at 20 m s^{-1} to 30 m s^{-1} to avoid premature solidification at the sprue.

5.2 Pressure Measurements

Experimental measurements on the gooseneck of Fig. 4(b) showed that pressure requirements increased according to a square law as anticipated from equation 1 above, following the line OX (Fig. 3). The point X represented the equilibrium flow rate, where the gooseneck-nozzle and machine pressure was identical. After modification (Fig. 4(a)) pressures now fell on the line OY, so that the flow rate and nozzle exit velocity had been considerably increased. The results of the change are summarized in Table II. Note the large increase in energy of the metal emerging from the nozzle. This energy is available to produce high gate velocity and overcome pressure losses in the die itself.

Good agreement was obtained between calculation and experiment.

5.3 The Effect of Pressure Losses in the Injection System on Machine Capacity

Pressure has to be supplied to the metal so that design gate velocity and flow rate is obtained. When flow ceases, the metal in the cavity remains molten and experiences the static system pressure, which must be resisted by the die locking system. If the required pressure can be reduced by say 25%, due to correct design of the metal flow system, then the locking force can also be reduced by 25%. A smaller machine can be used for a particular job, thus reducing production costs. In addition energy is saved in both the injection and locking parts of the machine. A hypothetical case is described in (8), and an actual case in 5.1 above.

5.4 Inertia Effects in Gooseneck and Nozzle

Die flashing can also be induced by excessive pressure due to the deceleration of metal in the gooseneck and nozzle. Alternatively this energy can be absorbed by metal flow through restricted overflow gates on the casting, which also assist in maintaining cavity pressure during fill. This topic is discussed in a previous paper (2). In general, large passage sizes and low metal velocity reduce the inertia effects, as well as reducing pressure losses. Inertia effects are particularly troublesome in large machines, due to the long flow channels involved.

6 FLOW PROBLEMS IN DIE

Experiments have shown that the pressure required to fill the die can be predicted (8). Current work is concerned with computer analysis of modern sprue and runner designs from the point of view of heat transfer and molten metal flow.

7 CONCLUSION

Basic principles of fluid mechanics have been largely ignored in the past. It has been shown that they can be applied to predict machine and die performance in the die casting process.

8 ACKNOWLEDGMENT

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