The Premature Wearing of a Bos Lance

1. INTRODUCTION

In the Basic Oxygen Steelmaking process, a water-cooled oxygen lance is lowered into the furnace to a predetermined height above the surface of the molten metal, and oxygen blown at a velocity of about Mach 2 onto the molten metal bath. The high velocity is used to achieve good penetration into the bath so that impurities such as carbon, phosphorous and manganese are efficiently removed by oxidation.

Figure 1 shows a lance tip which is typical of those used in BOS operations. It is about 300 mm in diameter, made of copper and has three Mach 2.2 oxygen nozzles arranged in an equilateral triangle. The lances invariably wear at the corner of the oxygen nozzles (see Figure 2). This wear makes the lance blow "softly", making it necessary to operate the lance closer to the surface of the molten metal. Eventually the lance must be discarded due to either inefficient use of oxygen as a result of the poor blowing characteristics, or water leaks caused by the erosion breaking into the water jacket.

The following aims were put to the Mathematics-in-Industry Study Group:

(1) Develop a heat transfer model for heat flow through the lance tip.

(2) Investigate the water cooling of the lance tip.

(3) Analyse the design of the supersonic oxygen nozzle.

(4) Investigate the possible mechanisms of the erosion around the nozzle.

Smooth operation of the BOS process requires a lance tip life of around 300-400 heats, but currently most tips are removed from service after only 60-80 heats. Research on this problem is being undertaken at BHP Melbourne Research Laboratories. Experimental work has been done on the flow of the cooling water, resulting in the inclusion of guide vanes in the water passage in the lance tip, but in spite of the significant improvement in water flow only a slight change in the wear resulted. Recently a lance was instrumented with thermocouples and the temperature at six positions in the copper and four points in the cooling water recorded every second during operation of the lance in the BOS vessel. Figure 3 shows the graph of the

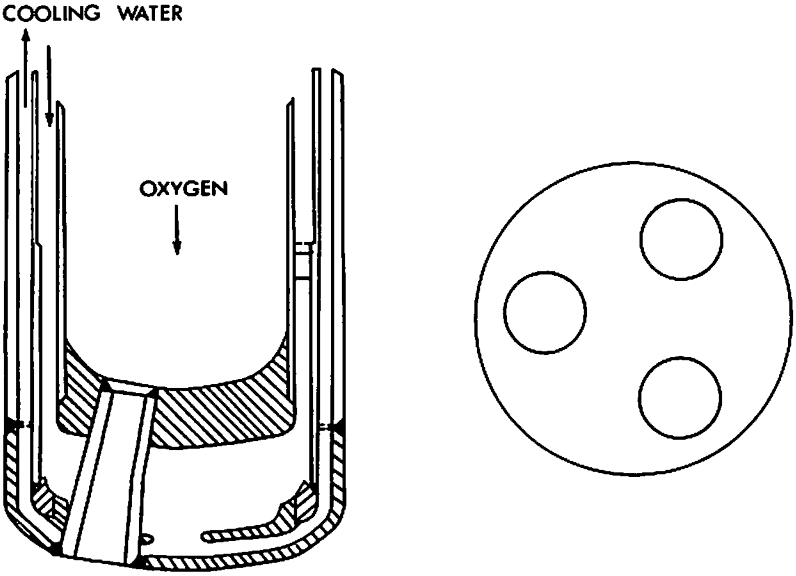

Figure 1: A typical three nozzle oxygen lance tip.

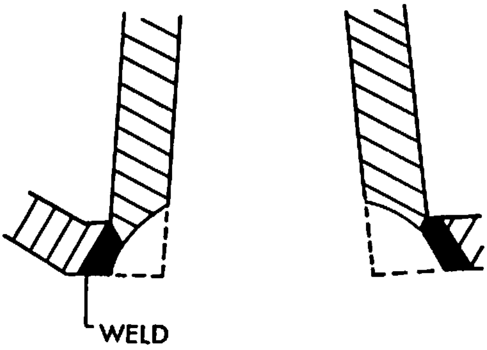

Figure 2: Wear on oxygen nozzle.

temperature at two locations in the lance tip during a heat.

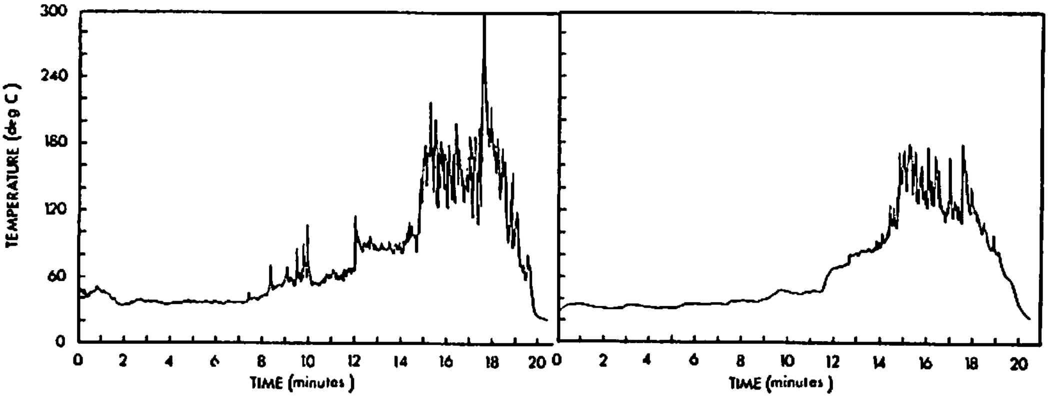

Figure 3: Temperatures in the copper lance tip 2 mm below the outer surfaces; (a) and (b) are at points 12 mm and 40 mm respectively from the edge of an oxygen nozzle.

2. HEAT INPUT INTO THE LANCE TIP

It is a simple matter to determine the amount of heat flowing into the tip of the lance since it is equal to the amount of heat dissipated to the cooling water. If M is the mass flow rate, c_p is the specific heat, and ΔT is the temperature rise of the cooling water as it passes through the tip, then heat is dissipated at a rate

$$Q = Mc_p\Delta T .$$

The difference between the inlet and outlet water temperatures ΔT generally increases as the heat progresses, reaching a maximum of 3-5 °C a few minutes before the end of the heat. Typically $M = 80$ kg/sec, and for water $c_p \simeq 4.2$ kJ/kg °C giving $Q \simeq 1.0$-1.7 MW. This is the heat input to the copper lance tip, and since this has an area of approximately 0.2 m^2, the maximum average heat flux is in the range 5.0-8.5 MW/m^2.

Because of the high temperatures inside the BOS vessel, radiation can be expected to be a significant mechanism of heat input to the lance. Assuming the vessel walls are at the same temperature T_1 °K as the molten metal, the heat flux reaching the lance tip at a temperature T_2 °K is approximately (Chapman, p.424)

$$q = \epsilon\sigma(T_1^4 - T_2^4) ,$$

where $\sigma = 5.67 \times 10^{-8}$ W/m^2°K^4 is the Stefan-Boltzman constant and ϵ is the emissivity of the surface of the lance. For oxidised copper $\epsilon \simeq 0.7$, and assuming the values $T_1 = 1873$ °K and $T_2 = 573$ °K one obtains $q \simeq 0.5$ MW/m^2.

Another mechanism of heat input is convection from the hot gases produced by the chemical reactions in the vessel. These gases are estimated to be at a temperature of about 3000 °C. We assume the usual expression or convective heat transfer

$$q = h(T_s - T_f) ,$$

where T_s is the temperature of the surface of the lance tip, again assumed to be 300 °C, and $T_f = 3000$ °C is the temperature of the gases. For forced convection of gases the heat transfer coefficient h lies in the range 10-500 W/m^2°C (Chapman, p.13) and, using the largest value, one obtains $q = 1.4$ MW/m^2.

Even though the estimates of radiation and convection are on the high side, only a small proportion of the total heat input has been accounted for. All graphs of temperature in the copper exhibit a lot of "spikes" (see Figure 3). A closer examination of these spikes reveals several interesting characteristics. The temperature rise is very rapid - although temperature readings were taken at most one second apart and at times only 150 milliseconds apart, the rise in temperature almost always occurred between two readings. However, the decay time is of the order of several seconds (the decay time for a square wave input is of the order of 0.2 seconds). A particular spike is not frequently seen by all thermocouples so the cause is often a local effect. The time period between spikes is on average about 5 seconds. These characteristics are all consistent with drops of molten metal splashing on the relatively cold surface of the lance and solidifying to an equilibrium depth determined by the rate of heat removed from the superheated metal shower. The lance tip normally has a coating of iron of between about 5 and 15 mm in thickness.

Examination of the temperature graphs show that there is more splashing near the oxygen nozzles than in the centre of the lance tip. This can be explained by an overall circulation in the neighbourhood of the oxygen jets as shown in Figure 4. Drops of molten metal will be carried with the flow, but due to their inertia, the larger drops will tend to move in an almost straight path and hit the lance near the edge of the nozzle.

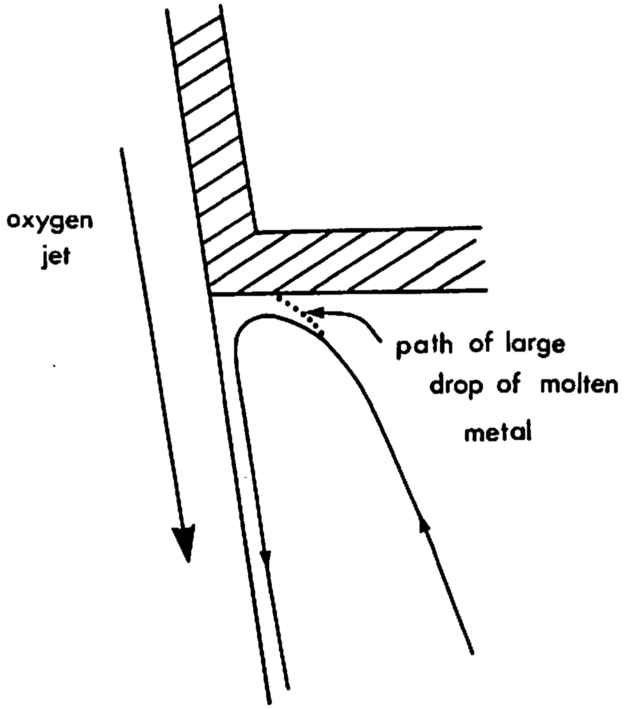

Figure 4: Splashing of the lance tip near an oxygen nozzle which is not worn.

This splashing of the lance cannot supply all of the unexplained heat input. If m kg/sec of molten metal hits the surface of the lance and all solidifies, it will give up heat at the rate

$$Q = m(L + c_s \Delta T) ,$$

where L is the latent heat per unit mass of the metal, c_s is the specific heat and ΔT is the drop in temperature of the metal. For steel the approximate values are $L = 2.7 \times 10^5$ J/kg, $c_s = 600$ J/kg °C, so for $\Delta T = 1600\text{-}300 = 1300\,^\circ C$ a splashing rate of 1 kg/sec would supply 1 MW or equivalently 5 MW/m^2 of heat to the lance tip. Clearly the splashing can only occur at a much lower rate, so there is some other mechanism of heat input. One possibility is the ignition of particles of iron near the lance giving local temperatures as high as 5000 °C with a consequent high radiation input.

3. THE WATER-COOLING OF THE LANCE TIP

The convective heat flux from the copper of the lance tip to the cooling water can be written as

$$q = h(T_s - T_b) ,$$

where T_s is the temperature of the wetted copper surface, T_b is the temperature of the bulk of the water and h is the heat transfer coefficient. For fully developed turbulent flow in pipes a widely used correlation is the Dittus-Boelter equation (Chapman, p.281)

$$Nu_D = 0.023\ Re_D^{0.8}\ Pr^{0.4} ,$$

where

$$Re_D = VD/\nu ,$$

$$h = Nu_D k/D ,$$

Pr is the Prandtl number, V the velocity, ν the kinematic viscosity and k the thermal conductivity of the water, and D is the hydraulic diameter of the pipe. For an annular space between two pipes, D is twice the width of the annular gap, so for the lance tip $D \simeq 0.03$. For water at about 25 °C, approximate values are $Pr = 6.1$, $\nu = 0.89 \times 10^{-6}$ m^2/sec and $k = 0.61$ W/m °C. From a frame by frame examination of high speed film of flow experiments, researchers at BHP-MRL have found that the cooling water flows through the tip at a velocity of approximately 30 m/sec. These values give $Re_D = 10^6$, $Nu_D = 2.7 \times 10^3$ and $h = 5 \times 10^4$ W/m^2 °C.

The above correlation is based on flow in a smooth straight pipe whereas the flow in the lance tip is over rough surfaces and has sharp turns including a reversal in direction around the baffle. Accordingly we would expect the heat transfer coefficient to be at least an order of magnitude larger. If $h = 10^6$ W/m^2 °C, the interior surface of the copper would be, on average, less than 10 °C above the water temperature. This value is consistent with the measured temperatures.

4. WEAR OF THE OXYGEN NOZZLE

The regular nature of the wear around the oxygen nozzles suggests that it is caused by some mechanism other than melting alone. The concave surface suggests the existence of a vortex as shown in Figure 5. Our conjecture is that particles of iron, small enough to be carried by the flow, find their way into the vortex, and, because of the presence of oxygen from the adjacent oxygen jet, ignite. Burning particles of iron can reach a temperature of 5000 °C, and as they are so close the resulting radiation will melt the surface of the copper which will then be eroded by the flow over it, the erosion perhaps being exacerbated by the abrasive effect of particles carried by the flow.

This suggested mode of erosion is essentially the way in which copper is cut with an oxygen torch. When steel is cut using an oxygen-acetylene torch it is actually burnt away, with the burning of the steel supplying most of the heat to bring the adjacent material up to ignition temperature. Copper does not burn below its melting point of about 1080 °C, and an oxygen-acetylene torch cannot provide enough heat to melt anything other than a thin sheet because of the high conductivity of copper. However introducing small particles of iron into an oxygen rich flame generates sufficient heat to melt the copper.

Assuming the mechanism described above, the wear can be eliminated by stopping the particles of iron from reaching the vortex, eliminating the vortex, or by keeping oxygen out of the region. Suggestions to achieve one or more of these included rotating the material in the vessel, giving the oxygen jets swirl, and placing auxiliary jets around the oxygen nozzle. However the best suggestion was to "sheath" the oxygen jet with a reducing gas such as methane or hydrogen, so that there is sufficient reducing gas in the vortex to

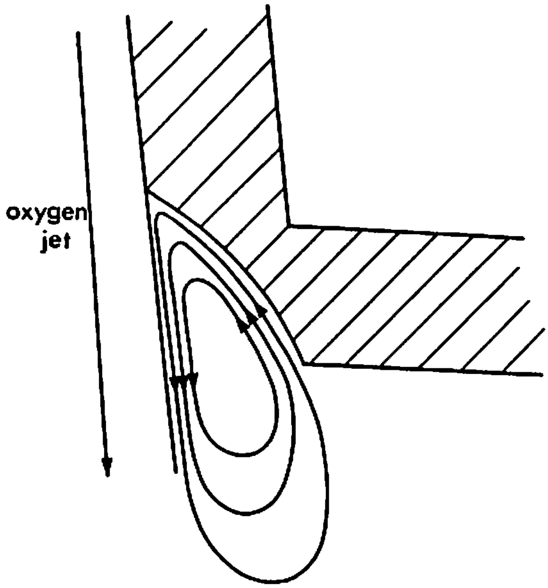

Figure 5: An illustration of the streamlines in the vortex surrounding the oxygen nozzle.

remove the oxygen and consequently prevent the burning of the particles of iron. This idea has the added advantage that the surface of the copper would not oxidise to cupric oxide, which is black, so reducing the heat input due to absorbed radiation.

The technique of adding methane around the oxygen nozzle is not new; it is briefly mentioned in a paper originally published in Russia by Kuz'min. However Dr Doug Ford of Memtec must be thanked for independently thinking of this idea, and more importantly for explaining why it works!

5. CONCLUSIONS

The following conclusions were reached:

(1) In view of the difficulty in determining the mechanism of heat input to the lance tip and the random nature of the splashing, the development of a heat transfer model seems impossible.

(2) The water cooling seems to be adequate.

(3) Burning of iron particles near the oxygen nozzle and the associated fluid

mechanics is suspected of causing the wear. It is suggested that sheathing the oxygen jet in a reducing gas will eliminate the problem.

It is recommended that some experiments be performed to test whether or not the wear is being caused by burning of particles of iron. Firstly an inert gas could be blown through one nozzle - this should completely eliminate the wear. Secondly the oxygen jet could be sheathed in an inert gas, and although this should decrease the wear it probably will not entirely eliminate it because there will still be some oxygen near the orifice. Finally the oxygen jet should be sheathed with a reducing gas.

It was also suggested that the employment of a Quality Control consultant may be beneficial. BHP has already gathered a large amount of data on the wear of the lances and is continuing to acquire more. There is a wide spread in the lifetime of the lances, and it may be that there are some hidden factors that might help to explain this variation.

The question of the design of the supersonic oxygen nozzle was not addressed. There seems to be scope for some work to be done in this area.

REFERENCES

Chapman, A.J., *Heat Transfer*, 4th edition, Macmillan (1984).

Kuz'min, A.L., *Prolonging Life of Water-Cooled Oxygen Lances*, Steel in the USSR (1985).