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# Erosive Wear Problems

## 1 INTRODUCTION

Many bulk particulate materials that have to be conveyed are very abrasive, such as silica sand, alumina, cement and fly ash. As a consequence, the pipeline, bends and various components that are exposed to impact by the gas-solid flows have to be designed and specified such that the problem is minimized to an acceptable level. It is not uncommon for steel bends, installed in a pipeline conveying an abrasive material, to fail in a matter of hours. The problem relates to abrasive materials and it is essentially the hardness of the particles that dictates the magnitude of the potential problem.

It must be stressed that it is virtually impossible to eliminate erosive wear if an abrasive material has to be conveyed. By the correct choice of materials of construction and design, and conveying conditions, however, the problems can generally be reduced to an acceptable level, with the support of an appropriate maintenance program.

### 1.1 Erosive Wear

Abrasive wear is associated with sliding contact between surfaces. In bulk solids handling plant abrasive wear is a major problem at hopper walls and in chutes, where materials slide over such surfaces. Erosive wear results from the impact of particles against surfaces. Typical erosive wear situations in bulk solids handling plant are in the loading and off-loading of materials, and with free fall onto surfaces. The blowing of materials into cyclones; their loading into hoppers and onto chutes; and off-loading from hoppers, conveyor belts and bucket elevators; are common examples. These are all cases where particles can impact against surfaces and cause erosive wear, rather than slide against a retaining surface and cause abrasive wear.

In pneumatic conveying systems, bulk particulate materials are physically transported by air. Bends in pipelines, therefore, are particularly vulnerable to erosive wear, as are diverter valves and any other surface against which particles are likely to impact, including the pipeline itself to a limited extent. Where a pressure difference might exist on a plant, in the presence of abrasive particles, erosive wear will also occur, if there is a flow of air. A particular example here is with rotary air locks and screws used to feed materials into positive pressure pipelines. Even isolating valves will wear if they are not completely air-tight.

## 1.2 Related Problem Areas

Erosion represents a major problem, not only in bulk solids handling plant, but in many other areas. In thermal power plant pulverized fuel causes erosive wear of supply lines and nozzles, and the resulting fly ash is a problem with respect to boiler tubes. Both pneumatic and hydraulic conveying of particulate materials in pipelines can result in severe erosion problems, and aircraft, rockets and missiles are eroded by rain drops and ice particles. The area that has probably received most attention, however, is aircraft engines, and in particular helicopters, for dust ingestion can cause considerable damage, and has resulted in several catastrophic failures in service.

### *1.2.1 Data Sources*

Information on erosive wear comes from a very wide range of sources, therefore. Until recent years little was known of the fundamental mechanisms of the erosion process or of the variables that influence the problem. There are, in fact, so many variables that influence the problem that advances have only been made by the development and use of specially designed erosive wear testing rigs. In these a wide range of powdered and granular materials have been impacted against a wide range of surface materials over carefully controlled conditions of velocity, particle concentration, temperature, impact angle, etc.

Many studies have been of a general nature with a view to getting a better understanding of the basic mechanisms of the process, and for this purpose numerous single particle impact investigations have been undertaken. Other studies have been conducted for specific purposes, and so the range of variables investigated can be extremely wide. For particle impact velocity, for example, tests have been carried out at about 3 to 10 ft/s for hydraulic transport, from 3000 to 7000 ft/min for pneumatic conveying, from 300 to 1500 mile/h for aircraft applications, and up to 18,000 mph for rockets.

## 2 INFLUENCE OF VARIABLES

There are many parameters associated with both the impacting particles and the surface material that can have an effect on erosive wear. In some cases the variables are inter-related and so need to be considered in groups in these situations. A review of the most important variables is given to provide some guidance on their influence on component specification and conveying conditions.

### 2.1 Impact Angle and Surface Material

A curve presented by Tilly [1] and shown in Figure 20.1 illustrates the variation of erosion with impact angle for two different surface materials and is typical of the early work carried out to investigate the influence of these variables.

Both surface materials showed very significant differences in both erosive wear rate and the effect of impact angle. These materials do, in fact, exhibit characteristic types of behavior that are now well recognized. The aluminum alloy is typical of ductile materials: they suffer maximum erosion at an impact angle of about 20° and offer good erosion resistance to normal impact. The glass is typical of brittle materials: they suffer severe erosion under normal impact but offer good erosion resistance to low angle, glancing impact.

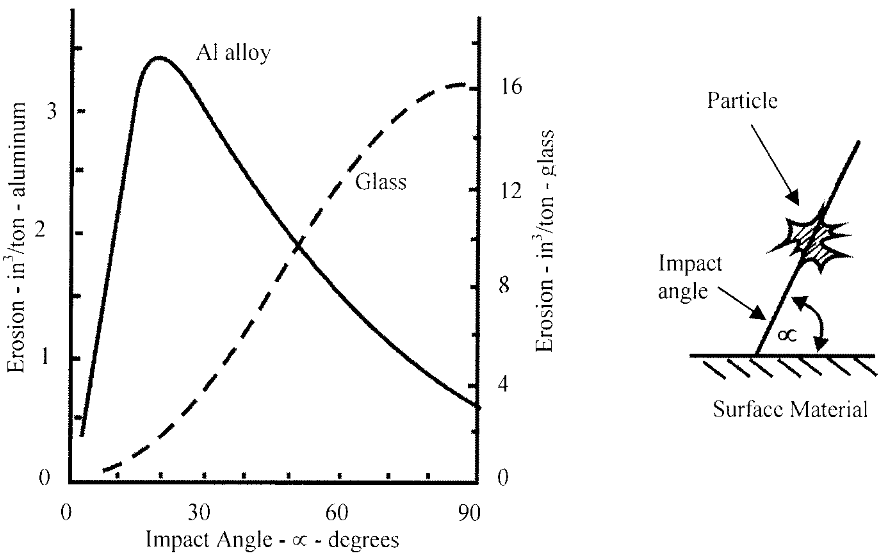



**Figure 20.1** Variation of erosive wear with impact angle for various surface materials.

The vertical axis on Figure 20.1 is in terms of the volume of surface material eroded, in cubic inches, per ton of particles impacted against the surface, in order to provide a more useful basis of comparison for the two materials. It will be noted that the erosive wear rate for the glass is magnified by a factor of five. Impact angle is clearly defined in the particle/surface sketch alongside.

These particular tests were carried out with sand particles sieved to between 60 and 125 μm and impacting at about 20,000 ft/min. The value of velocity is indicative that the tests were not carried out for pneumatic conveying, but aircraft applications. That brittle and ductile materials respond to erosion in very different ways can be clearly seen from Figure 20.1, and it is obvious that different mechanisms of material removal must be involved.

The influence of impact angle and the different response of ductile and brittle materials to erosive wear is an aspect of the problem that will be considered at many different points throughout this chapter. The relationships can be used to explain a number of observed phenomena in erosive wear, and are particularly useful in predicting the possible behavior in new and untried situations.

### *2.1.1 Theories Proposed*

From early thoughts on the matter it was suggested that for ductile materials (annealed low carbon steel, copper, aluminum, etc) material removal is predominantly by plastic deformation. No cracks propagate ahead of the cutting particle and the volume removed is due entirely to the cutting action of the particle, rather like the cutting edge of a machine tool.

For brittle materials (glass, basalt, ceramics, cast iron, concrete, etc) it was thought that material removal is in a large part due to the propagation of fracture surfaces into the material.

These erosion processes, however, have subsequently proved to be not quite as straightforward as this. Photographs taken of impact craters, produced as a result of single particle impact studies, have shown clear evidence that melting has taken place [2, 3]. The melting only occurs over a small part of the impact crater, but it must be considered as being contributory to the erosive wear process. This is considered further, in relation to heat treated surface materials, later in this chapter.

## 2.2 Velocity

Of all the variables that influence the problem of erosive wear, velocity is probably the most important of all, not least because pneumatic conveying requires a given minimum value in order to convey materials. It is generally recognized that erosive wear is dependent upon a simple power of velocity, rather like the influence of velocity on pressure drop, such as:

$$\text{Erosion} = \text{constant} \times (\text{velocity})^{n}$$

*2.2.1 Surface Material*

There has been much confusion as to the value of the exponent, and values of n ranging from two to six have been reported. Tilly and Sage [4] tested a wide range of different materials and obtained very good agreement with respect to the exponent, n, in each case. Their results are reproduced in Figure 20.2. This is a log plot and the slope of all the lines was approximately 2·3. The velocities, of course, are well above those generally encountered in pneumatic conveying systems, even at the lower end of their range.

The velocity exponent is now generally considered to be approximately 2·5, and although erosive wear resistance varies widely for different surface materials, as shown in Figures 20.1 and 20.2, the value of the velocity exponent remains reasonably constant at a value of about 2·5 for all surface materials, whether ductile or brittle.

*2.2.2 Bend Wear*

Few comprehensive erosion studies have been carried out exclusively in the velocity range appropriate to pneumatic conveying. Results from one extensive research program into the erosion of pipe bends in an actual pneumatic conveying system, at velocities appropriate to dilute phase suspension flow have been published [5].

Tests were carried out over a range of conveying air velocities from 3000 to 7000 ft/min and at solids loading ratios from 0·5 to 8. Two inch nominal bore steel bends having a bend diameter, D, to pipe bore, d, ratio of about 5:1 were eroded by large batches of silica sand having mean particle sizes of 70 μm (210 Mesh) and 230 μm (65 mesh).

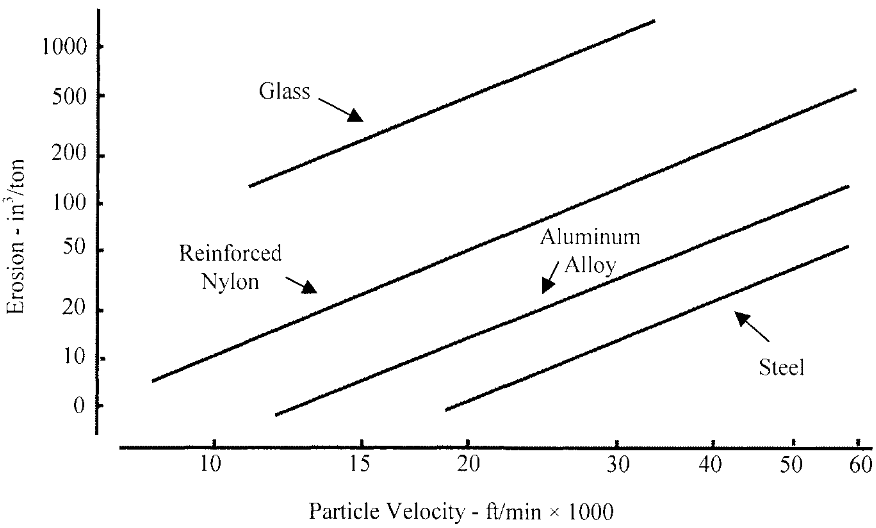



**Figure 20.2** Variation of erosion with velocity for various surface materials.

Over the ranges of conveying air velocity tested the velocity exponent was found to be very consistent at a value of about 2·65. A graph showing the influence of conveying air velocity on the specific erosion of the pipeline bends tested is given in Figure 20.3.

The erosion is in terms of the mass of metal eroded from a bend per ton of sand conveyed through the bend. With a velocity exponent of 2·65 it means that the wear rate will increase by a factor of approximately six with a doubling of the air velocity. This explains why the curve rises so steeply on Figure 20.3.

If a positive pressure conveying system operates at a pressure of about 15 psig, a doubling of the velocity will be achieved in a single bore pipeline discharging to atmospheric pressure. With a vacuum conveying system a doubling in velocity will be achieved with a system exhausting at about 7½ lbf/in$^2$ absolute. In either type of system a bend at the end of the pipeline will wear six times as fast as a bend at the start of the pipeline.

If an abrasive material is to be conveyed, therefore, it would always be recommended that the pipeline be stepped to a larger bore part way along its length in order to limit the maximum value of velocity that is achieved, in order to minimize the erosive wear of bends towards the end of the pipeline. It is essential, of course, that the step to the larger bore pipeline is correctly positioned along the pipeline, for if the velocity falls below the minimum value of conveying air velocity at the step to the larger bore pipeline, the pipeline is likely to block at this point.

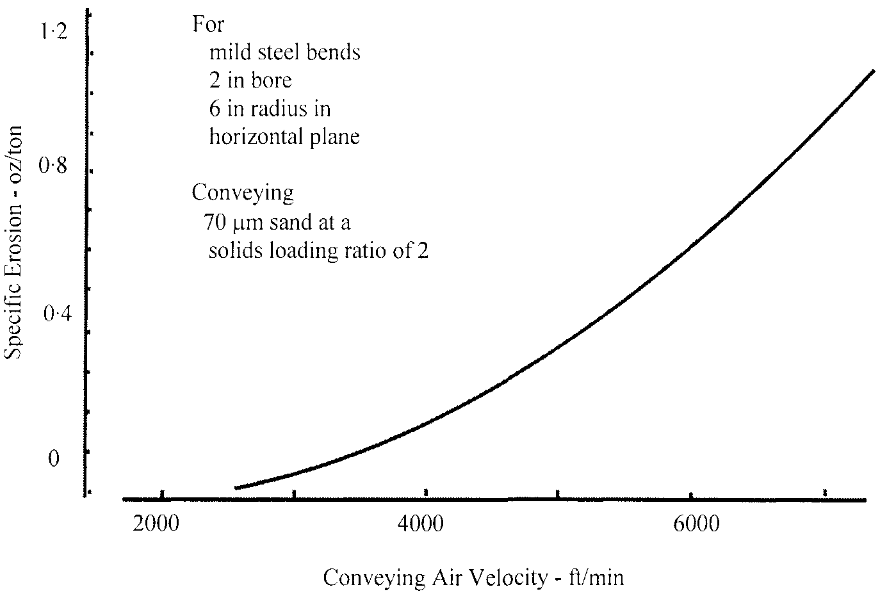



**Figure 20.3** The influence of velocity on the erosive wear of bends in a pneumatic conveying system pipeline.

Figure 20.3 shows quite clearly that excessively high conveying air velocities should be avoided. It also shows the benefits of conveying with low velocity air, and hence the potential of low velocity, dense phase flow in this respect. With the bends reported in Figure 20.3, tested at a solids loading ratio of two, bend failure occurred when about 2 oz of metal was eroded from the bend. The bend wall thickness was about 0·15 inch.

In Figure 20.4 the conveying capacity of these bends, in terms of the mass of sand that could be conveyed through the pipeline before bend failure occurred, is presented. From this it will be seen that with a conveying air velocity of about 6000 ft/min only 3 ton of sand could be conveyed before bend failure.

## 2.3 Particle Size

The general consensus of opinion with regard to particle size is that there is a threshold value of wear rate which, for velocities appropriate to pneumatic conveying, occurs at a particle size of about 60 μm. Below this size wear rate reduces, but for particle sizes greater than 60 μm it remains constant. Results of work carried out by Tilly [6] are presented in Figure 20.5. This shows that the threshold value increases with increase in velocity. The work was carried out for an investigation into the erosion of aircraft engines, which explains the high velocity range. A shot blast type of test rig, in which abrasive particles were impacted against flat plates, was used for the purpose.

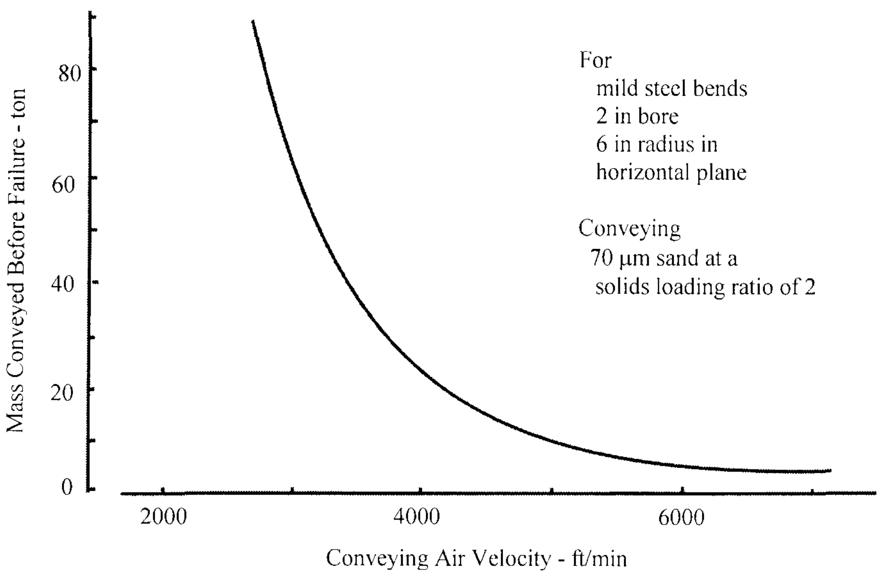



**Figure 20.4** The influence of velocity on the conveying capacity of the bends shown in figure 20.3.

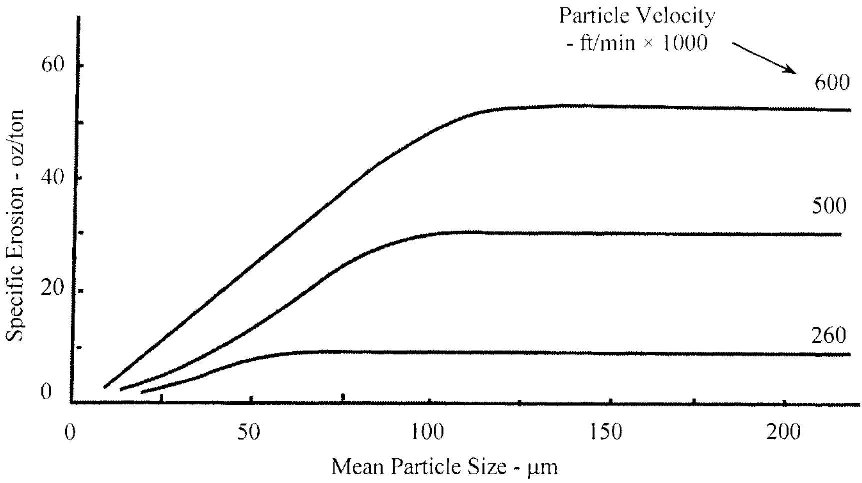



**Figure 20.5** The influence of particle size and velocity on erosion.

Wear rate here is expressed in specific terms, that is the mass of surface material eroded per unit mass of particles impacted. In a given mass of particles, the number of particles will reduce as the particle size increases, and so although the specific erosion remains constant with increase in particle size, the erosive wear per particle will increase approximately with the cube of the particle size. Little work has been undertaken with particles much larger than about 1000 micron (1 mm or 18 Mesh) in size and so it is not known to what particle size the threshold value remains constant.

### *2.3.1 Bend Wear*

Work carried out on actual pipe bends in pneumatic conveying system pipelines would tend to confirm this [7]. Batches of sand with mean particle sizes ranging from 70 to 280 μm were used in a program of conveying trials. Six test bends in the one pipeline were monitored for erosive wear, and the average mass eroded from each bend was found to be independent of particle size.

On an individual basis, however, the bends showed a very interesting trend. The degree of scatter in the results increased markedly with decrease in particle size, as shown in Figure 20.6. With the larger particles the wear rates were remarkably consistent, but with the finer particles the spread of the results was very wide.

It is believed that the finer particles are influenced by the secondary flows and turbulence that can be generated by the bends and that this causes accelerated wear of some bends, although there is no obvious reason why some bends were more vulnerable than others in the pipeline.

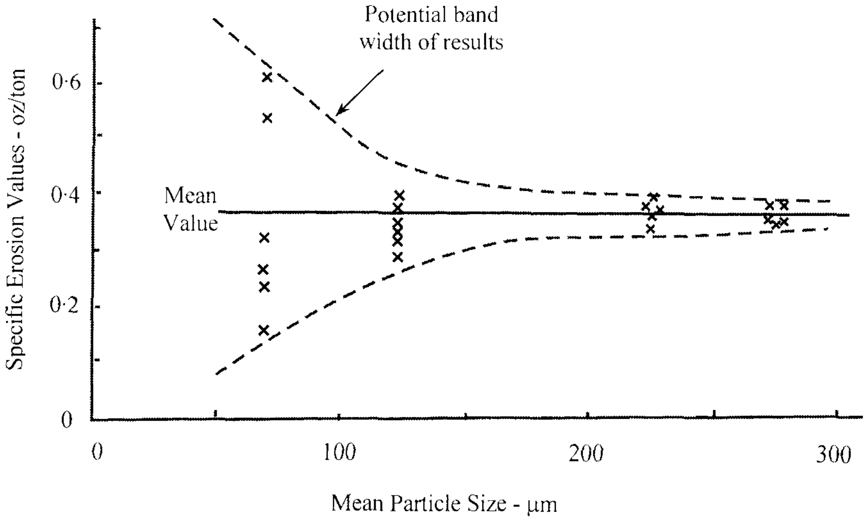



**Figure 20.6** The variation of individual specific erosion values with mean particle size for bends in a pneumatic conveying system pipeline.

This could well account for some of the premature failures that have been reported in situations where very fine materials have been conveyed. It was also found that the depth of penetration of the particles into the bend walls was a factor of two greater for the 70 μm sand as compared with the 280 μm sand. Since failure occurs when a given thickness of material is eroded, this parameter is potentially as important as specific erosion in pipe wear situations.

### *2.3.2 Fine Particle Wear*

Some researchers have suggested that particles below about 5 μm will cause little or no erosive wear. In pneumatic conveying this is probably a reasonable assumption, for particles below this size are likely to follow the air stream and not impact against a surface. The trend of the curves, representing the limits of the potential spread of the results in Figure 20.6, with respect to particle size is not known. It is suspected that the upper limit may reach a maximum at about 50 μm and then rapidly decrease.

## 2.4 Particle Hardness

The value of the particle hardness of the material being conveyed is the major indicator of the potential erosiveness of the material. Goodwin et al [8] investigated the influence of particle hardness on erosive wear with a rig in which abrasive particles were impacted against test plates. They found that erosion is related to hardness by the expression:

$$\text{Erosion} = \text{constant} \times H_p^{2.4}$$

where $H_p$ = particle hardness

It is generally considered, however, that there is a threshold value of particle hardness beyond which erosion remains essentially constant. This occurs at a particle hardness of about 800 kg/mm$^2$, and so materials with hardness values much greater than this would not be substantially more erosive than sand particles.

### *2.4.1 Bend Wear*

A sketch of the potential influence of particle hardness on the erosion of mild steel bends is given in Figure 20.7 [9]. It is derived for sharp angular particles, and the erosion is expressed in specific terms once again, that is oz/ton conveyed. The hardness values of typical materials, both potential conveyed materials and bend surface materials, have been superimposed for reference.

It will be noticed from this that coal is a very soft material and is unlikely to be a problem with respect to erosion. In reality, of course, both pulverized and granular coal are erosive materials. This, however, is due to the presence of non-combustible minerals, such as quartz and alumina in the coal, and not to the coal itself. With large tonnage flows, even small percentages of these highly abrasive minerals will cause severe wear.

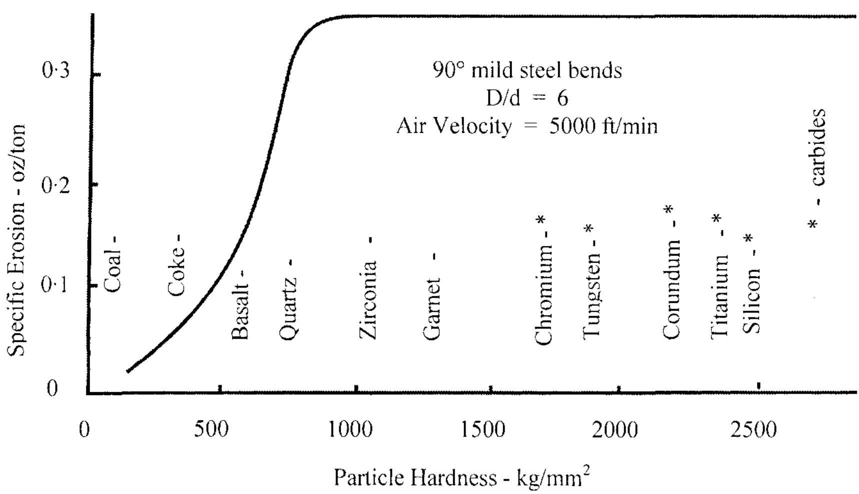



**Figure 20.7** The influence of particle hardness on the erosion of bends in a pneumatic conveying system pipeline.

A similar situation applies to pulverized fuel ash, and other materials containing small percentages of similar contaminants, such as barite and wood chips.

### *2.4.2 Hardness Measurement*

A knowledge of particle hardness is essential, therefore, particularly at the design stage of a plant, since it gives an indication of the need to take steps to avoid excessive wear of key system components. Scratch hardness is the earliest known type of hardness test, and in its simplest form is the ability of one solid to scratch, or be scratched, by another.

The method was first proposed on a semi-quantitative basis in 1822 by Mohs, who selected ten mineral standards, starting with the softest - talc (scratch hardness 1) and ending with the hardest - diamond (scratch hardness 10). Because of its simplicity it is still widely used today as a reference for potential erosive wear of plant by conveyed materials. This has become known as the Mohs hardness scale, but divisions along the scale are clearly not all of the same magnitude.

Since the Mohs scale proved too coarse for the measurement of the hardness of general engineering metals, quantitative tests of the static indentation type were devised, mostly based on the use of pyramids. Equipment is available for carrying out such tests with fine particulate materials, but because of its complexity, the Mohs scale is still used today for many bulk solids handling applications. Metal hardness, of course, is usually referred to in terms of the value indicated by one of these indentation methods. Fortunately sufficient research has been undertaken to relate the hardness as measured by any of these methods to the Mohs scale number. Such a relationship is shown in Figure 20.8.

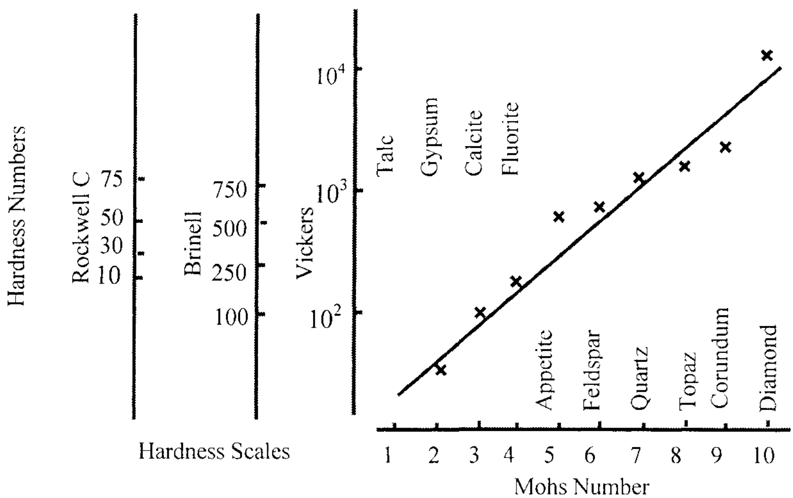



**Figure 20.8** Relationship between Mohs, Vickers, Brinell, and Rockwell hardness scales.

## 2.5 Surface Material

A number of surface materials were included in Figures 20.1 and 20.2. In Figure 20.2 it was shown that, for a given impact angle, the effect of velocity was similar for each material. Figure 20.1, however, showed that impact angle could have a very different effect, with the ranking of different materials changing significantly with impact angle. From these figures it is clear that surface hardness is not necessarily the main parameter to be considered in selecting materials for erosive wear resistance.

### *2.5.1 Steels - Heat Treated*

There is a wealth of information in the field of abrasive wear on the relationship between surface material hardness and wear resistance for metals. One of the earliest of these [10] shows that the hardness value of annealed metals provides an approximate estimate of their resistance to abrasive wear. Cold working fcc metals to higher hardness values has essentially no effect on abrasive wear resistance, and hardening and tempering carbon steels to achieve higher hardness levels does not result in a corresponding increase in wear resistance.

Finnie [11] was the first to show that such a relationship might exist in the field of erosive wear, but Finnie et al [12] were the first to produce a hardness to wear resistance relationship similar to those presented for abrasive wear. Results of their work are presented in Figure 20.9.

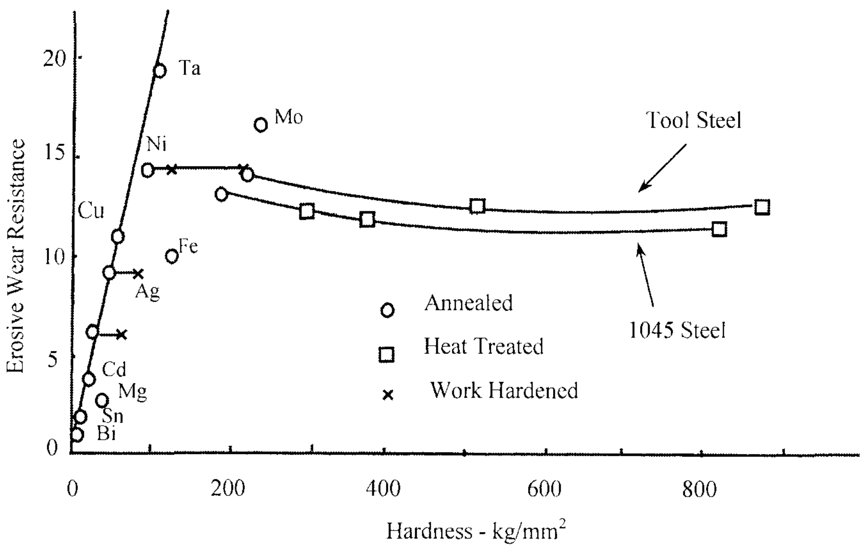



**Figure 20.9** Variation of erosive wear resistance with indentation hardness for various surface materials.

The range of materials that they considered was rather limited but the shape and trends of the curves were similar. Several researchers have commented on the possibility of micro-melting occurring over a small part of the indented surface, as mentioned in relation to Theories Proposed in section 2.1.1 above. This could partially over-ride the effect of heat treatment and micro-structural changes.

### *2.5.2 Resilient Materials*

Resilient materials, such as rubber and polyurethane, are commonly used in erosive wear situations. Although the hardness of the surface material is generally far lower than that of the particles impacting against the surface, they derive their erosive wear resistance from the fact that they are able to absorb most of the energy of impact by virtue of their resilience.

Mason et al [13] tested mild steel, nylon and Linatex (a proprietary material containing 95% natural rubber) in a shot blast impact testing machine. Alumina particles were impacted at different angles over a range of velocities. They showed that the nylon and rubber exhibited typically ductile behavior, with respect to impact angle, similar to mild steel. Their erosive wear results, with respect to air velocity, are shown in Figure 20.10.

These show that natural rubber is superior to mild steel at velocities below about 24,000 ft/min, but above this value the performance of the rubber rapidly deteriorates. It is suspected that beyond a certain impact energy level the rubber is no longer able to absorb the energy. As a result the wear mechanism probably changes to one of tearing and possibly burning because of the heat generation.

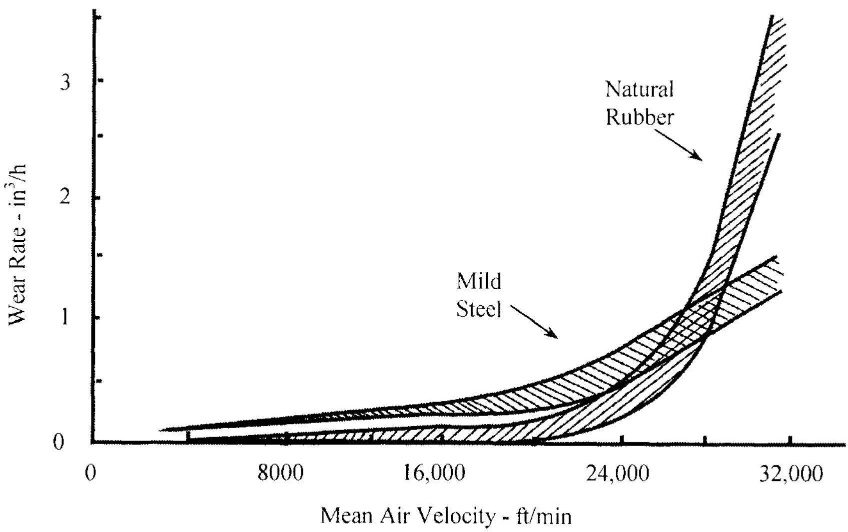



**Figure 20.10** The influence of air velocity on wear rate for mild steel and rubber surface materials.

This point is considered further in the section dealing with Industrial Solutions to the problem, where the use of rubber is considered as a bend wall material.

### *2.5.3 Hard Materials*

Hard brittle materials are generally used in cases of severe erosive wear. Materials used include Nihard, basalt and ceramics. Nihard is an abrasion resistant white cast iron. It contains about 6% Ni, 8·5% Cr, 1·7% Si and 0·5% Mn and the structure can be refined by chill casting. The material has a Brinell hardness of 550 to 650, which is equivalent to a Vickers hardness of about 750 $kg/mm^2$.

Basalt is a volcanic rock which can be cast into sections and used for lining surfaces, and although widely used for lining chutes and hoppers, it is often used for straight pipeline and bends. After casting, the material is heat treated to transform it from an amorphous into a crystalline structure. This is a naturally hard material with a hardness, according to the Mohs scale of 7 to 8, which is equivalent to a Vickers hardness of about 720 $kg/mm^2$. Basalt consists of approximately 45% silica and 15% alumina, with the rest made up of oxides of iron, calcium, magnesium, potassium, sodium and titanium.

Of the materials used for providing erosion resistance, alumina based materials are probably most common. A typical material consists of 50% aluminum oxide, 33% zirconium oxide and 16% silicon oxide. The general industry specification today is an alumina content of 85%, although higher alumina contents can be supplied. It has a hardness of 9 on the Mohs scale, which is equivalent a Vickers hardness of about 2000 $kg/mm^2$. Like basalt, these materials can also be cast into moulds of the required shape.

## 2.6 Particle Concentration

Particle concentration is a variable that has received little attention in basic research work on the subject, with the general opinion being that erosion decreases only very slightly for a large increase in concentration. Concentrations investigated, however, have generally been very much lower than those encountered in pneumatic conveying, even with dilute phase conveying. This is because most research work on erosive wear has been with atmospheric dust loadings for aircraft applications.

### *2.6.1 Bend Wear*

The general explanation for the gradual reduction in erosive wear with increase in solids loading ratio is that as the particle concentration increases, fewer impacts occur between the particles and the bend wall surface due to the interference of an increasing number of other particles. From work on the erosive wear of pipe bends, the following relationship for erosive wear has been derived [14]:

$$\text{Mass Eroded} \quad = \quad \text{constant} \times (\text{solids loading ratio})^{-0{\cdot}16}$$

It has also been found that the depth of penetration of particles into the bend wall surface varies with particle concentration, or solids loading ratio, as with particle size reported earlier [14]. As the solids loading ratio increases, the particles appear to focus on a smaller area of bend wall surface such that the rate of penetration of the particles increases. In terms of the mass of metal that has to be eroded from a bend before failure occurs, the following relationship has been determined [14]:

$$\text{Mass Eroded at Failure} = \text{constant} \times (\text{solids loading ratio})^{-0.74}$$

By combining the data on the mass eroded from the bends, with that on the depth of penetration of the conveyed material into the bends, it is possible to determine a relationship for the mass of material that can be conveyed through a bend before failure occurs [14]. Data for the bends investigated is presented in Figure 20.11.

This is similar to the data presented on the influence of velocity presented in Figure 20.3. It will be seen from Figure 20.11 that as the solids loading ratio increases the life expectancy of the bends reduces quite considerably. Although the specific erosion rate decreases with increase in solids loading ratio, the influence of the increase in penetration rate has an over-riding effect.

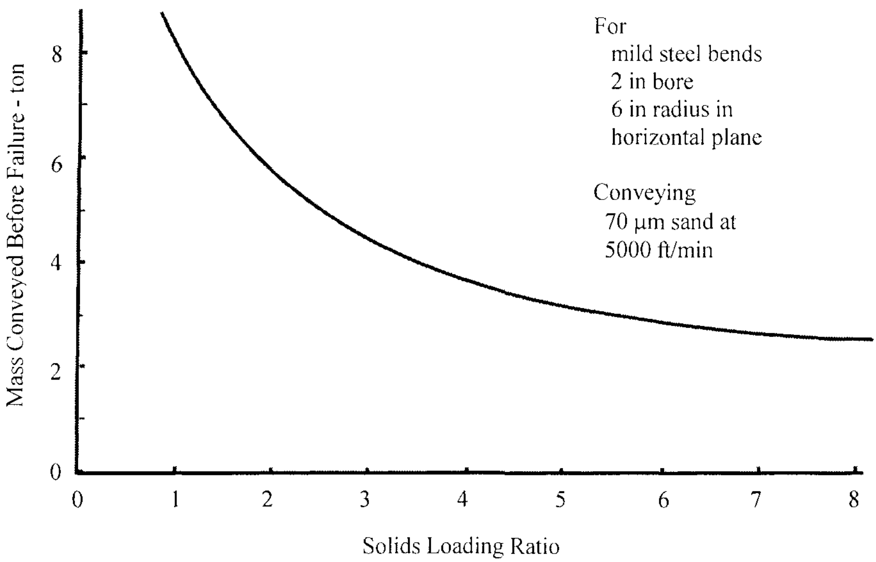



**Figure 20.11** The influence of solids loading ratio on the conveying capacity of bends in a pneumatic conveying system pipeline.

It was reported earlier, with respect to particle size, and Figure 20.6, that the degree of scatter of the results increased considerably with decrease in particle size. A similar phenomenon was observed with regard to solids loading ratio, with the degree of scatter increasing considerably with increase in solids loading ratio. In terms of component life, therefore, both particle penetration rate and possible scatter in the results are potentially as important as mass eroded. Once again there was no obvious explanation for the occurrence, but it is possible that eddies produced and turbulence generated increase with increase in concentration.

## 2.7 Particle Shape

The influence of particle shape on mass eroded has been reported by many researchers. The result is much as one might expect, with smooth and rounded particles causing much less erosion than sharp angular particles, under similar conditions of impact velocity, surface and particle hardness, etc. For test work on the erosive wear of pipe bends in pneumatic conveying system pipelines there is generally a need to re-circulate the conveyed material.

As a result of re-circulating the material it degrades, and the sharp angular corners and edges of the fresh material are gradually worn away, and so become more rounded and hence less erosive. Typical data on the erosive wear of pipeline bends is presented in Figure 20.12 [15].

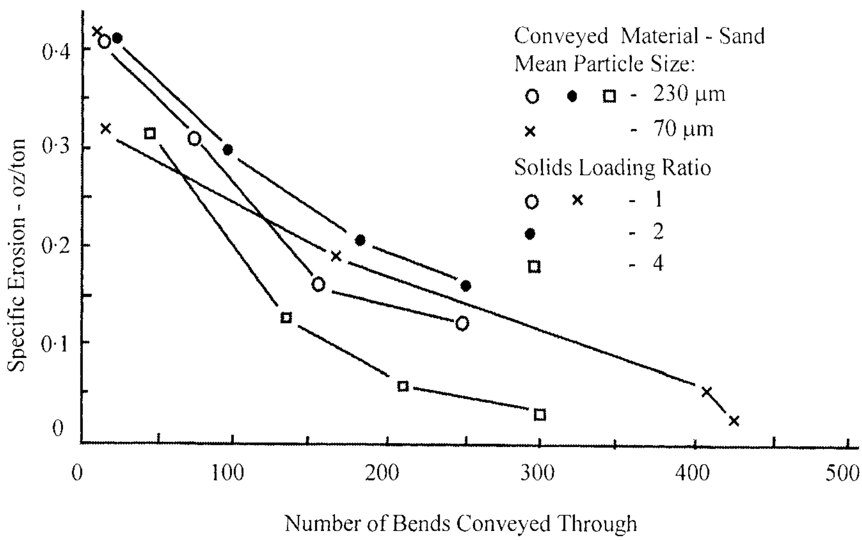



**Figure 20.12** The effect of particle degradation and wear on the erosion of bends in a pneumatic conveying system pipeline.

The conveyed material was silica sand and the results from four different test programs are included. The average value of conveying air velocity in each case was about 5000 ft/min. Since it is likely that most of the wear and degradation to the conveyed material in dilute phase conveying can be attributed to the bends in the pipeline, the horizontal axis is in terms of the accumulative number of bends through which the sand was conveyed. The average spacing of the bends, for reference, was about 15 ft.

### 2.8 Surface Finish

It is generally thought that a highly polished surface will reduce the rate of erosive wear, but it must be emphasized that this is effectively just an incubation period. It will generally only have the effect of reducing the wear rate initially. Once the material surface starts to wear it will have little further influence on the steady state erosion rate.

Brittle materials that have porous surfaces are particularly vulnerable to erosive wear. This can result from the casting process of these materials if gas bubbles are allowed to form. If a gas bubble results in particles impacting at an angle close to 90° extremely rapid wear will result in that area [16].

## 3 INDUSTRIAL SOLUTIONS AND PRACTICAL ISSUES

To a certain extent the problem of bend wear in pneumatic conveying system pipelines is a problem with which industry has learnt to live. There are a number of ways by which the severity of the problem can be reduced, but a number of factors relating to the material conveyed and the system itself have to be taken into account. Expense is obviously a consideration, some methods may lead to a reduction in the conveying capability of the plant, and if the material being conveyed is friable then a solution that additionally minimizes the effect of degradation must be sought.

### 3.1 Pipeline Considerations

The volumetric flow rate of air specified and the pipeline bore chosen are of major importance, for the two have to be selected so that the resulting conveying air velocity is acceptable. The problem is that air is compressible and so its value is significantly affected by pressure. This represents a particular difficulty in high pressure systems, where the air pressure can drop from 20 to 40 psig at the start of the pipeline to atmospheric at the other end.

As the pressure of the conveying air decreases along the length of the pipeline its density decreases, with a corresponding increase in volumetric flow rate, and hence velocity. In order to keep the velocity to within reasonable limits, stepped pipelines are often employed. A similar situation exists with negative pressure systems when operating under high vacuum. Stepped pipelines were considered in some detail in Chapter 9.

If, for example, the air supply pressure in a positive pressure conveying system is 45 psig, and the conveying line inlet air velocity is 3000 ft/min, the conveying air velocity will approximately quadruple to about 12,000 ft/min at the end of the pipeline in a single bore line. A four fold increase in velocity will result in an almost forty fold increase in mass eroded from the bends.

This explains why bends near the end of a pipeline will generally fail in a much shorter time than those near the start of the pipeline. If a dense phase system was specifically installed to overcome the problem of erosion, a stepped pipeline for such a system would be almost essential if a high air supply pressure was used.

## 3.2 Bend Wear

By the very nature of the transport process, pipelines used for pneumatic conveying systems are prone to wear when abrasive materials have to be conveyed. In dilute phase, materials are conveyed in suspension in the air, and a relatively high conveying air velocity must be maintained in order to keep the material moving, and so avoid pipeline blockage.

The main problem relates to the wear of bends in the pipeline, and any other surfaces where particles are likely to impact as a result of a change in flow direction. Bends provide pneumatic conveying systems with their flexibility in routing, but if the material is abrasive and the velocity is high, rapid wear can occur.

### *3.2.1 Influence of Bend Geometry*

Bends are available in a wide range of geometries, in terms of bend curvature, from long radius bends to tight elbows and mitered bends. Because bends are so vulnerable to wear there have been many developments and innovations for reducing the problem.

The influence of bend geometry, for radiused bends, has been investigated over a wide range of D/d values [17]. The results for 90° mild steel bends are shown in Figure 20.13. The bends were eroded by sand, conveyed at a solids loading ratio of two and with a conveying air velocity of 5000 ft/min.

The results can, to a certain extent, be predicted from the data presented in Figure 20.1 which shows the influence of impact angle on erosive wear for both ductile and brittle materials. It is possible to calculate the relationship between the bend geometry (D/d) and the impact angle and the results of such an analysis are given in Figure 20.14. This clearly shows the nature of the problem.

With sharp, or short radius bends, having a D/d ratio of 2:1, for example, it will be seen from Figure 20.14 that the particles will impact against the bend wall at a fairly steep angle. At a high impact angle, as will be seen from Figure 20.1, erosive wear will not be too severe for a ductile material and so it can be expected that the bend will not wear too rapidly.

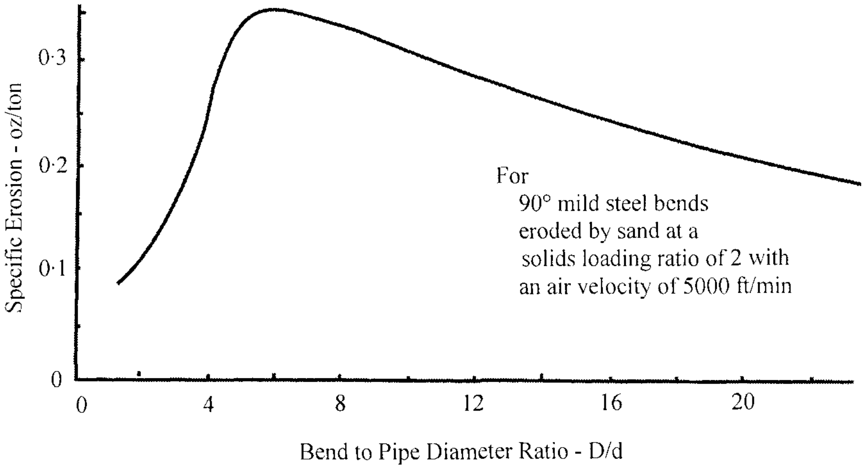



**Figure 20.13** The influence of bend geometry on the erosive wear of pipeline bends.

Bends with a D/d ratio of 6:1 correspond closely to the worst case from the data in Figure 20.13. The particles impact against the bend wall at an angle of about 30° and for a ductile material this will result in severe erosion. The particle impact against the wall for the bends with a D/d ratio of 24:1 is at a much shallower angle. If the impact angle is relatively small erosion will not be too severe, and so it can be expected that the bend will not wear too rapidly.

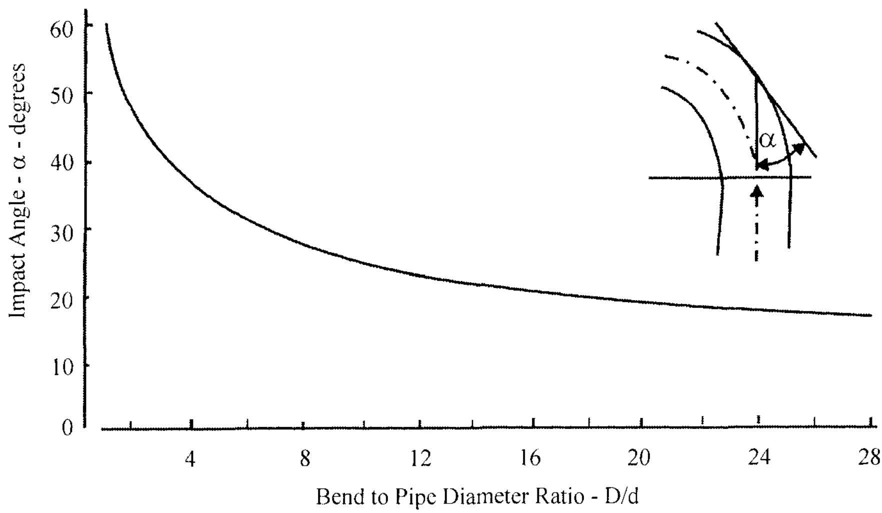



**Figure 20.14** Influence of bend geometry on particle impact angle.

#### 3.2.1.1 Long Radius Bends

A very low impact angle is an essential pre-requisite for minimizing erosion, particularly in the case of brittle surface materials. In the case of ductile materials, because of the remarkably steep increase in erosion with very small increase in impact angle, as shown in Figure 20.1, exceptionally long radius bends would be required. Bends with varying curvature have been proposed to overcome this particular problem.

For ductile materials long radius bends are not likely to be a viable proposition. For brittle materials, however, such as basalt and cast iron, they are essential, as mentioned above. A common method of providing a long radius bend is to make the bend in segments. By this means the bend will be lighter and much easier to fit into the pipeline.

Since the majority of the wear will be at the initial point of impact point, only one or two sections need be replaced should the bend fail. It is also possible to reverse and inter-change segments and so extend the overall life of the bend. Segments can be made in 45°, 30° and 22½° sections. A four section long radius bend is shown in Figure 20.15.

#### 3.2.1.2 Short Radius Bends

With very short radius bends the angle at which the material impacts against the bend wall will be fairly high, as shown in Figure 20.14.

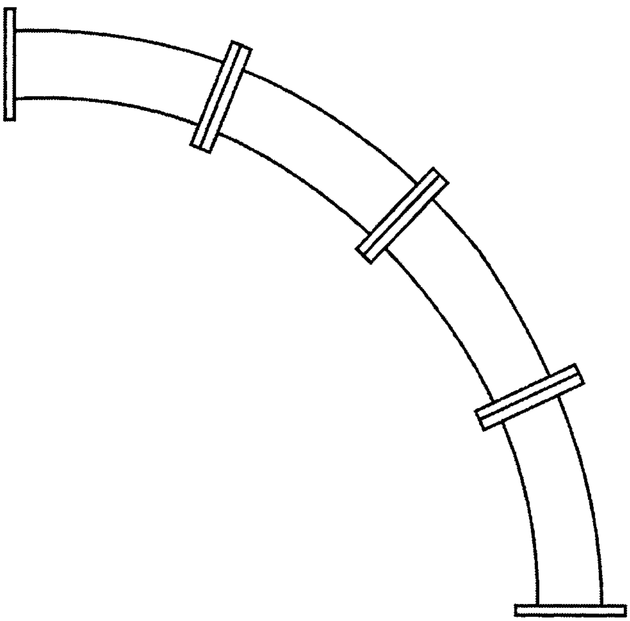


**Figure 20.15** Long radius bend with replaceable and interchangeable 22½° segments.

Although this will not be suitable for brittle surface materials, ductile materials, because of their improved erosion resistance at high impact angle often give reasonable service in use, if the conveyed materials is not too abrasive.

Three major problems have to be taken into account, however, before using very short radius and similar bends. The more severe the impact of the material against the bend wall the greater will be the problem of degradation if the material is friable. The introduction of a very short radius bend will probably also increase the conveying line pressure drop, which will mean that the material mass flow rate will have to be reduced to compensate. A very short radius bend, and those that are designed to trap the conveyed material, may require a slightly higher value of conveying line inlet air velocity to ensure that the pipeline does not block.

A very cheap and often effective solution to the erosion problem is to use a blanked tee-piece or mitered bend (D/d = 0) made from regular pipe. Such a bend is shown in Figure 20.16. This gives a simple right-angled bend in the line, and so consideration has to be given to the problems of purging the line clear, should this be necessary, added degradation (see next chapter) and pressure drop (see section 5.3 in Chapter 8).

The material being conveyed fills the blanked section of the tee and part of the bend so that much of the material being conveyed impacts against itself and not against the pipe wall. Should the line block at the bend, access can be gained from the blanked section to facilitate clearing. Such bends generally fail at the start of the exit section of pipeline, due to the turbulence generated, and so it would be recommended that a thicker section of pipeline should be incorporated here.

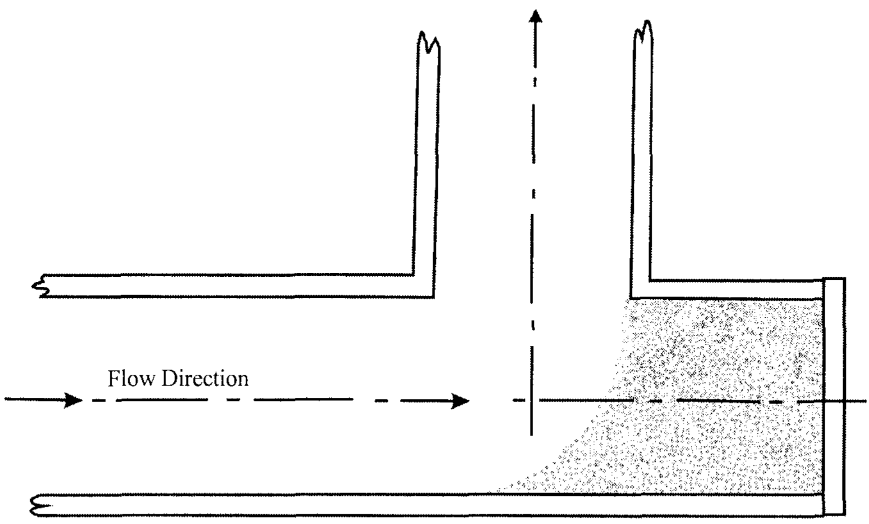



**Figure 20.16** Sketch of tee piece bend.

A more sophisticated version of this was developed in the early 1970's and is known as the Booth bend after its originator. This is a very short radius cast bend which incorporates a shallow depression. This allows material to collect in the bend and so subsequent material flowing through the pipeline will impact against itself. A sketch of the bend is given in Figure 20.17.

Another, more recent version, is a short radius bend with a large recessed chamber in the area of the primary wear point. It is claimed that this acts as a vortice and that material is constantly on the move in this pocket, thereby providing a cushioning effect.

Consideration, however, has to be given to the location and orientation of the bend. Such a bend located close to the material feed point may require a slightly higher conveying line inlet air velocity. Limited published test work on the bend has shown the pressure drop across the bend to be quite high (see section 5.3.1 of Chapter 8). A sketch of the bend is given in Figure 20.18.

*3.2.2 Air Injection*

A number of bend protection devices have been proposed that incorporate the injection of air into a bend. The object of these is to deflect the impacting particles away from the bend wall. The main problem with this type of device in a pneumatic conveying line is that air injection has to be continuous at each bend.

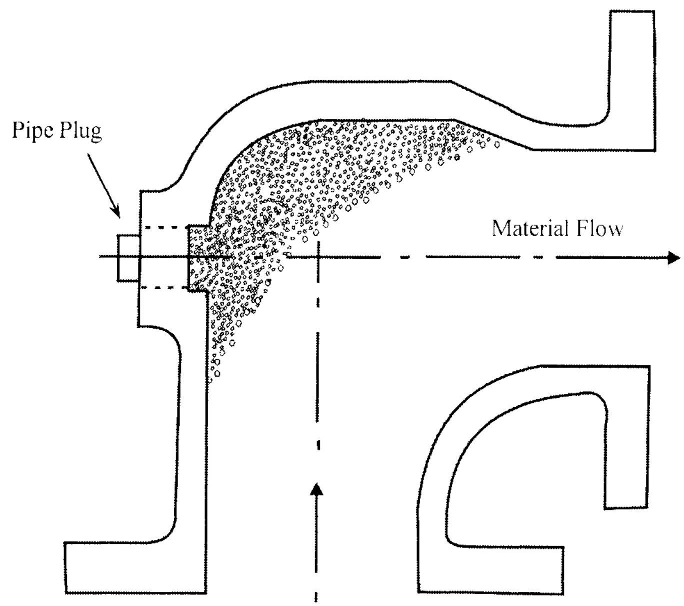



**Figure 20.17** Sketch of short radius bend with shallow depression.

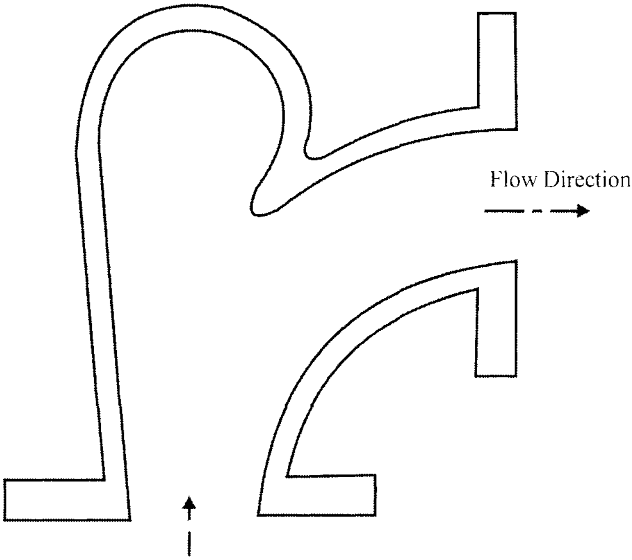



**Figure 20.18** Sketch of vortice pocket bend.

In a pipeline of constant bore this will result in a further increase in velocity, and since erosion is highly dependent upon velocity, this method does tend to aggravate the problem. The pipeline can be stepped to a larger diameter part way along its length, but this adds considerably to the cost of the plant and the complexity of its design, and so this method is rarely used.

### *3.2.3 The Use of Hard Materials*

Hard, brittle materials are generally used in cases of severe wear. Materials used include Ni-hard, basalt and ceramics, as discussed in the section on Hard Materials above. These materials can generally be cast or formed into sections, and in the case of non-metals, are used for lining pipes and bends. Care must be taken with cast materials, however, as mentioned above in relation to Surface Finish, for if a porous surface if obtained, rapid erosion can result. Because of the impact angle effect such bends do need to have a reasonably long radius.

### *3.2.4 The Use of Resilient Materials*

Resilient materials such as rubber and polyurethane are widely used in erosive wear situations. Although the hardness of the surface is often far lower than that of the material being conveyed, and impacting against the surface, they derive their erosion resistance from the fact that they are able to absorb much of the impact energy, without being permanently damaged, by virtue of their resilience, as mentioned earlier.

Several programs of tests have been carried out to compare rubber and steel bends in pneumatic conveying pipelines [18]. In one such program a pipeline was built in which several rubber and steel bends were alternately positioned at the corners of a test loop so that they could be tested at the same time for a direct comparison. Tests were carried out with lump coke and fine silica sand, each conveyed at a solids loading ratio of 10 and with a conveying air velocity of about 5000 ft/min. Figures 20.19 and 20.20 show the comparative wear effects of the coke and sand on the rubber and steel bends very well.

These are pipe section profiles taken at the point around the bend where either the bend failed or where the penetrative wear was a maximum. Each bend was two inch nominal bore, with a pipe wall thickness of 0·16 inch in the case of the steel bends and 0·40 inch in the case of the rubber bends. To illustrate the different erosive wear profiles the pipe wall has been magnified by a factor of 1·5 in relation to the pipe bore.

Figure 20.19 compares the pipe section profiles of the steel and rubber bends when eroded by coke. The rubber bends failed after about 50 ton of coke had been conveyed through them, at which time about 2·0 oz had been eroded from the bends. Only 1·1 oz had been eroded from the steel bends, however, and they would probably be capable of conveying another 50 ton before they would fail. In terms of potential service life, therefore, the steel bends could be expected to last twice as long as the rubber bends for the conveying of the coke.

Figure 20.20 compares the pipe section profiles of the steel and rubber bends when eroded by the sand. In this case the steel bends failed after only 3·8 ton of the sand had been conveyed through them, at which time about 1·9 oz had been eroded from the bends.

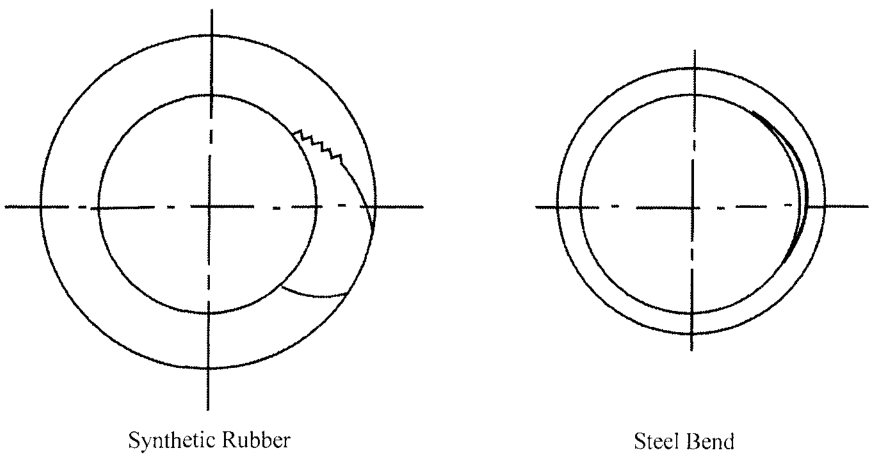
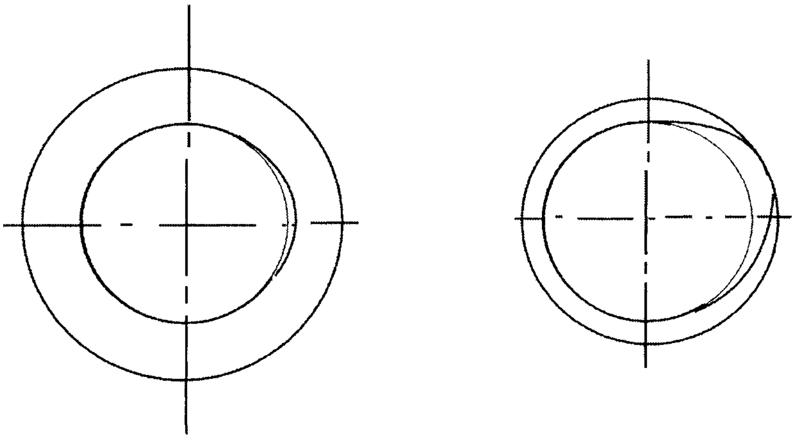



**Figure 20.19** Comparison of bend section wear profiles for bends eroded by coke.



Synthetic Rubber                Steel Bend

**Figure 20.20** Comparison of pipe section wear profiles for bends eroded by sand.

Only 0·35 oz was eroded from the rubber bends at this stage, and they were quite clearly capable of handling considerably more sand before they would fail. In terms of potential service life, therefore, the rubber bends could be expected to last about five times as long as the steel bends for the conveying of the sand.

Thus for bulk materials having a large particle size, such as lump coal, coke and mined and quarried materials, rubber bends can not be recommended for erosive wear applications, and certainly not in high velocity, dilute phase conveying applications. It is believed that there is a threshold value of impact energy that resilient materials such as rubber can withstand without suffering significant damage, as discussed in the section on Resilient Materials above. As either particle size or impact velocity increase the impact energy of a particle will increase. In relation to velocity this effect was shown quite clearly in Figure 20.10.

### *3.2.5 Surface Coatings*

A wide range of materials can be applied to existing surfaces, and in many cases they are applied to erosion resistant surfaces, such as Ni-hard, to give added protection. Polyurethane, which cures at ambient temperature, is often used. This can be sprayed, or applied in putty form by trowel, which is particularly useful for repairing eroded surfaces. Hard-facing metal alloys, tungsten carbide and a range of oxide ceramics can be applied to surfaces by means of flame spray coating.

Some of these materials have very high hardness values, and combined with the fact that the surfaces can also be very smooth, they can provide good erosion resistance. The surface coatings, however, can generally be applied only in thin layers and so once this is penetrated the bend will rapidly fail.

*3.2.6 Wear Back Methods*

Wear back methods are potentially the cheapest and most effective means of suppressing bend erosion and are commonly used in industry. A channel welded to the back of a bend and filled with concrete, as shown in Figure 20.21, is probably the most common method adopted. When the outer surface of the original steel bend erodes, the concrete will generally extend the life of the bend for a reasonably long time. It is essential, however, that the wear back covers as much as possible of the outer bend surface, for bends can be holed over a wide range of both bend and pipe angles.

The only problem with this type of solution is that when a primary wear point is established in the concrete at the initial impact point, deflection of particles can result, and these may cause erosion of the inside surface of the bend. The bend may well fail through erosion of the inside surface long before the material has penetrated the concrete. Secondary and tertiary wear pockets in long radius bends may also cause the material to be deflected against the wall of the following straight length of pipe and cause this to fail. These points are considered in more detail below.

A similar method of prolonging bend life is to sleeve the main bend with another pressure-tight bend, which is also shown in Figure 20.21. This provides protection for both the inner and outer surfaces of the bend. When the inner bend fails the space will fill with the material being conveyed. Subsequent impact will mostly be conveyed material against conveyed material and so erosion of the inside surface is not likely to cause failure of the bend.

This is not likely to work where the erosion at the secondary wear point is so great that very large areas of the bend are eroded away. In this case it might help if the annular gap was filled with a concrete, possibly made from the conveyed material itself.

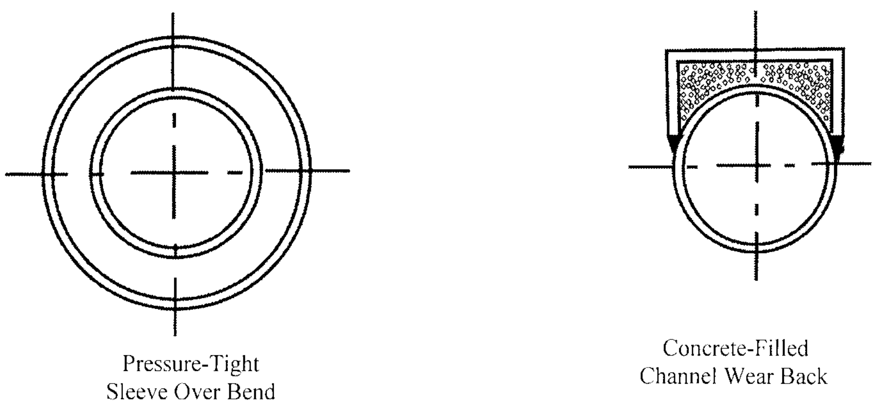



**Figure 20.21** Wear back methods of bend reinforcement.

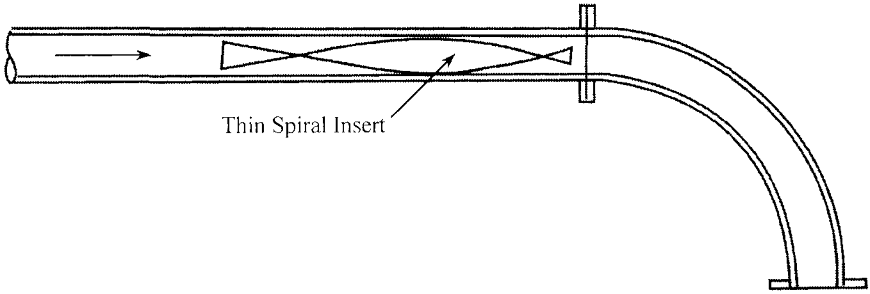



**Figure 20.22** Bend protection by use of sacrificial inserts in the preceding straight length of pipeline.

### *3.2.7 The Use of Inserts*

Considerable protection can be provided for a bend by positioning a sacrificial insert in the pipeline just prior to the bend. An insert made of a flat strip and twisted through 180°, for example, and shown in Figure 20.22, will ensure that the material impacts against the insert prior to impact against the bend. The velocity of the particles will be reduced after impact with the strip and the presence of the strip will prevent the particles from focusing on a small area of the bend. Such a strip should offer little resistance to flow and should last for a reasonable period of time, since the wear would be very evenly distributed over the entire surface of the strip [19].

### *3.2.8 Ease of Maintenance*

In terms of ease of maintenance, very short radius bends have the particular advantage of their much lighter weight. These can generally be removed and changed by two men without the use of special lifting equipment. Bends with the provision of replaceable wear backs are also very useful in this respect, such as that shown in Figure 20.23, as the bend itself does not have to be removed or replaced.

These are usually made of Ni-hard or similar material. The backs must be replaced on a regular basis, however, and not when failure occurs. If they are left until failure occurs, much of the body may have worn away and it may not be possible to guarantee an air-tight seating. If the material being conveyed is potentially explosive, the possibility of the bend wearing to a point where it will be incapable of withstanding the explosion pressure generated must also be considered.

With large bore pipelines square section bends are often fabricated, and in such a manner that the outer wall can be removed, as illustrated in Figure 20.24. This allows for easy replacement. Alternatively the backing plate can be made of a different material, or be given a lining of a costlier material, to resist the erosive wear. Laminated backings of rubber and steel are often used.

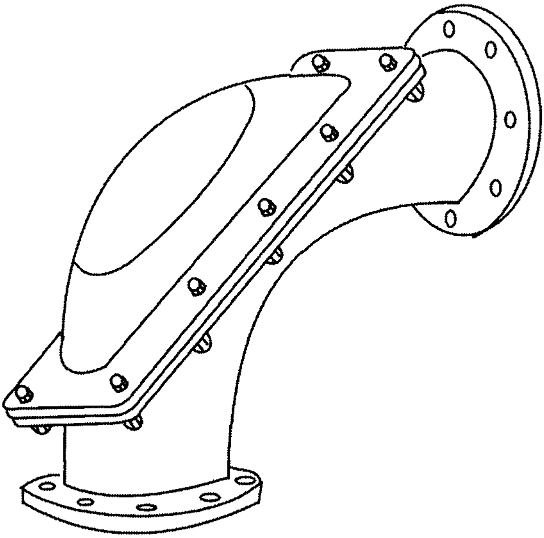


**Figure 20.23** Bend with reinforced and replaceable back.

### 3.3 Wear Patterns and Deflecting Flows

Mason and Smith [20] carried out tests on one and two inch square section 90° bends with a flow of alumina particles from vertically up to horizontal. The bends were made of Perspex and were constructed with substantial backing pieces.

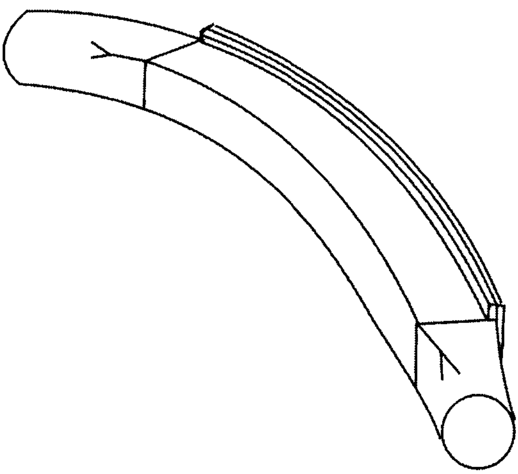


**Figure 20.24** Fabricated bend with square section and replaceable outer wall.

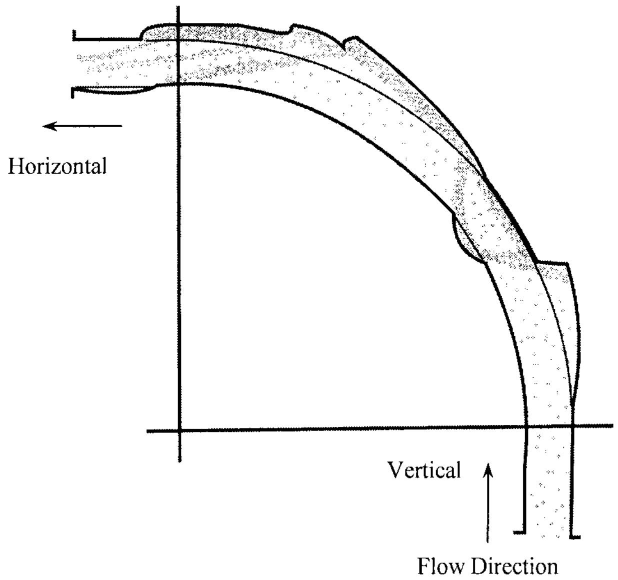



**Figure 20.25** Wear and flow pattern for an eroded bend.

The substantial reinforcement was provided in order that the change in flow pattern and wear over a period of time could be visually observed. The results from one of their tests are given in Figure 20.25.

With a new bend the particles tend to travel straight on from the preceding straight pipeline until they impact against the bend wall. After impact they tend to be swept round the outside surface of the bend. They are then gradually entrained in the air in the following straight length of pipe. In Figure 20.25 the flow pattern is shown after substantial wear has occurred.

This shows quite clearly the gradual wearing process of a bend and the effect of impact angle on the material in the process. Erosion first occurred at a bend angle of 21° which became the primary wear point. After a certain depth of wear pocket had been established, however, the particles were deflected sufficiently to promote wear on the inside surface of the bend, and then to promote a secondary wear point at a bend angle of 76°.

A small tertiary wear point was subsequently created at an angle of 87°. If such a well reinforced bend were to be used in preference to replacing worn bends, the deflection from the latter wear points would probably cause erosion of the straight pipe section downstream of the bend. Because this pattern of particle deflection in worn bends is now well recognized, some companies manufacture steel bends with thicker walls and a typical example is shown in Figure 20.26.

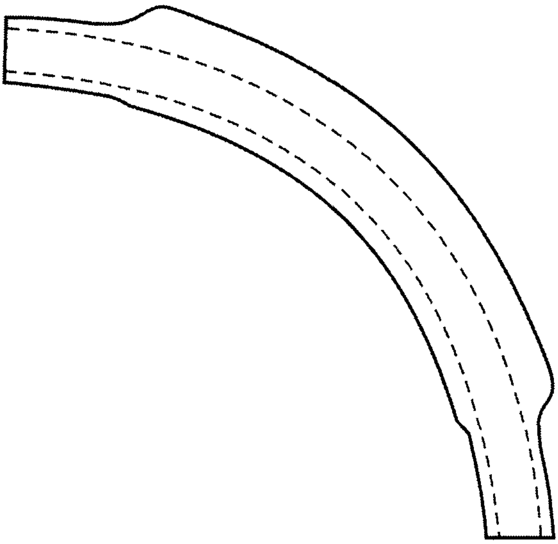


**Figure 20.26** Bend with reinforced walls.

This particular bend is also slightly thicker on the inside surface to allow for the fact that particles can be deflected to the inside surface, as illustrated in Figure 20.25, particularly in smaller diameter pipelines.

### *3.3.1 Influence of Impact Angle*

The curve in Figure 20.1, of erosion against impact angle for the aluminum alloy, provides a means by which an interpretation of the type of wear shown in Figure 20.25 can be obtained. The outer wall of the bend presents a surface at a low impact angle to the particles issuing from the preceding vertical straight pipe run, and as Perspex is a ductile material rapid erosion takes place. Gradually the impact angle at this primary wear point changes to almost 90°. From Figure 20.1 it will be seen that ductile materials suffer relatively little erosion under normal impact, and this explains why little further erosion takes place at this point.

The conveyed material can be seen quite clearly to be deflected out of this primary wear pocket. Because of this abrupt change in direction, however, it is no longer swept around the bend as before, but impacts on the inside surface of the bend. It is then deflected to the outer wall again, and because the low impact angle is maintained here, the erosion at this point is far greater than that at the primary wear point.

Mason and Smith [20] also mention that a conventional bend design, used to avoid plant shut down due to wear, is to reinforce the outside of the bend with a mild steel channel backing filled with a suitable concrete, as illustrated in Figure 20.21. They included a radiograph of such a four inch bore pipeline bend and this shows a primary wear pocket developing in precisely the same manner as for the

Perspex bend test. It is believed that the bend ultimately failed through erosion of the inner surface due to material deflection from the primary wear point.

## 3.4 Wear of Straight Pipeline

Straight pipeline is rarely a problem with regard to erosive wear, although there are specific circumstances where it should be taken into account. Reference has already been made above to the deflection of particles issuing from a well reinforced eroded bend. Similar deflections can be promoted from poorly aligned pipe sections, and large abrasive particles present a particular problem.

### *3.4.1 Following Bends*

It will be seen from Figure 20.25 that the straight section of pipeline, following a well reinforced bend, is liable to erosive wear. Although the angle of impact of the particles is generally low, for a ductile material low angle impact is likely to result in significant wear, because of the remarkably steep increase in erosion with very small increase in impact angle, as illustrated in Figure 20.1.

To extend the life of the pipeline following a bend, therefore, it is suggested that a short section of thick walled pipe should be placed between the bend and the main pipeline, as illustrated in Figure 20.27. The section of thick walled pipe following a bend does not have to be very long for the deflecting flow is soon dampened out. A 6 ft section is generally long enough for small bore pipelines, and something of the order of twenty pipe diameters should be allowed for larger bore pipelines.

Since the flow of deflected particles issuing from a bend will generally impinge constantly on the same area of the thick walled pipe it is also recommended that this short section of pipe should be connected by flanges to the bend and the following section of regular pipeline so that it can be rotated on a regular basis.

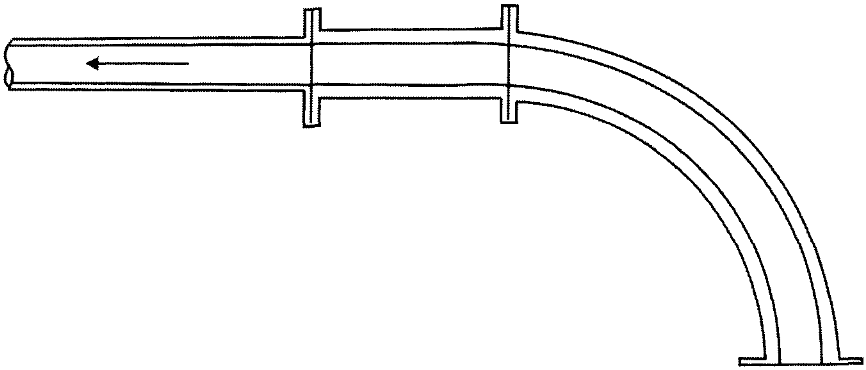


**Figure 20.27** Thick walled section of straight pipeline following reinforced bend.

This will both help to extend the life of this section of pipe and prevent a large wear pocket forming which could result in a further site for particle deflection to occur.

Hot dust laden gases from boilers and reactors are often passed through heat exchangers for generating steam. The tubes through which the gases flow often wear, and are generally very expensive to repair. The wear is usually only at the start of the tube. This is because the dusty gases on entry to the tube are in a very turbulent state and numerous particle impacts occur.

After a short distance the flow is effectively straightened out and little further pipeline wear occurs. An effective solution to the problem is to provide a sacrificial extension to the pipe array prior to the tube plate and the heat exchange section for flow straightening purposes.

### *3.4.2 Pipe Section Joints*

Misaligned flange joints, and welded joints with weld metal protruding inside the pipeline, as illustrated in Figure 20.28, can often lead to straight pipeline failure, particularly in small bore pipelines. It is a similar situation to the wear pockets formed in bends, since the step produced can result in particle streaming. This is particularly a problem if rubber hose is attached to steel pipe by means of pushing the hose over the steel pipe or hose clamp fitting. A small step will be formed and this can cause severe streaming of particles where the fitting presents a reduction in area to the oncoming flow.

### *3.4.3 Large Particles*

Small particles will generally be conveyed through a pipeline with little contact with the pipeline wall in dilute phase suspension flow, in the absence of flow streaming and turbulence promoting sites. With large particles, however, gravitational force has a much greater effect. Large particles can be conveyed quite successfully, but in horizontal flow they will tend to skip along the pipeline.

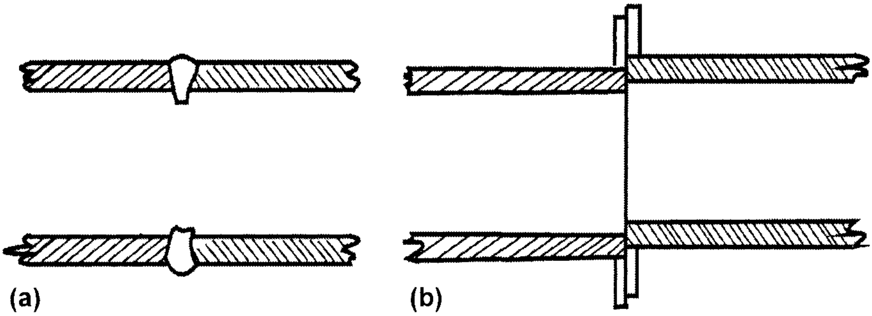



**Figure 20.28** (a) Welded and (b) flanged examples of erosion promoting sites at poorly jointed pipeline sections.

They will convey in suspension, but gravity will give them a low trajectory in their flow, and hence they will impact fairly frequently with the pipeline wall. The impact angle will be very low but, as has been discussed before, wear of ductile pipeline materials can be significant as a result of glancing impact from abrasive particles.

Erosive wear, as a result, will be concentrated along the bottom of the pipeline. Since it is not generally very convenient to reinforce a pipeline along its entire length, in order to overcome this problem, it is recommended that the pipeline should be rotated periodically. By this means the pipeline will last for a very much longer period of time. It is important to recognize this problem when the pipeline routing is being planned, however, for the horizontal sections of pipeline need to be located where convenient access can be gained to carry out the rotating process.

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