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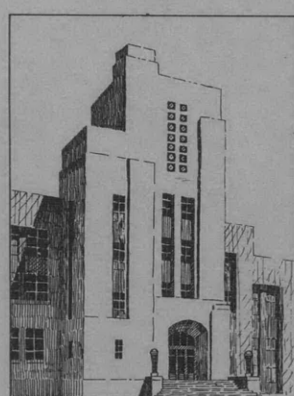
UNITED STATES NAVY

SEALED CONTACT JOINTS IN STATIONARY MACHINE PARTS

BY KARL TRUTNOVSKY



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SEALED CONTACT JOINTS IN STATIONARY MACHINE PARTS

(BERÜHRUNGSDICHTUNGEN AN RUHENDEN MASCHINENTEILEN)

by

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SEALED CONTACT JOINTS IN STATIONARY MACHINE PARTS

SUMMARY

A study of the nature of contact joints reveals the general possibilities of attaining complete tightness. The forces acting in a sealed joint can be approximately expressed by a characteristic number, which is also a gage of the relative amounts of material used in the joint. Various influences affecting this characteristic number are discussed. Clamped joints (shaped contact surfaces, gaskets, and molded packings), self-sealing joints, and the sealing of joints by welding are discussed, and directions are given for designing flanged joints.

INTRODUCTION

The purpose of sealed joints is to segregate spaces of different pressures from each other.

A sealed joint may be judged from many different viewpoints. Among these are tightness, durability, load requirements, space requirements, ease of dismounting, cost of installation and upkeep, safety of operation, strains, number of movements, mean sliding speed (Gleitgeschwindigkeit) of adjacent machine parts, peripheral speed, strength characteristics, coefficient of friction, resistance to wear, chemical resistance to wear, chemical resistance, ability to withstand variations in temperature, surface conformation, heat transmission coefficient of packing material or of the machine parts, and frequency of dismounting and lubrication, whether the joint is self-sealing or tightened by external forces. The importance of these individual factors varies with the purpose for which the joint is intended. A slight leakage in some cases may be unimportant, whereas in other cases, for example when poisonous fuels are being used, such leakage is not permissible. Moreover, an apparently negligible leak may become important when the system in question is in continuous operation over long periods.

MODE OF ACTION OF SEALED CONTACT JOINTS

Figure 1 gives an idea of the nature of contact joints (1).* In 1a is shown the unattainable ideal form of contact surfaces. Actually the surface conformation is governed by the manufacturing methods, Figure 2 (2). The interstices act as labyrinths, i.e., the flow that takes place is throttled, so that the loss due to leakage is a function of the cross section and number of the interstices (3). If it is possible to make the cross section equal zero within the circumference of a circle drawn around the point to be sealed a perfect joint results. This can be achieved by the following methods:

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* Numbers in parentheses indicate references at the end of the paper.

1. By deformation of the contact surfaces as shown in Figure 1e. This requires an increase of sealing force or a decrease of the contact surfaces in order to effect their elastic and permanent deformation.

2. By grinding the sealing surfaces to fit, as shown in Figure 1b. This increases the number and size of the points of contact.

3. By filling up the irregularities with a highly malleable plate or gasket, as shown in Figure 3 (2). The joint is then subjected to a sealing pressure, which stresses the gasket material past its elastic limit and causes it to flow. A purely elastic deformation is also possible, as when rubber is used.

4. By a chiefly plastic deformation of a packing ring, Figure 1d; by corresponding deformation of the contact surface, Figure 1c; or by deformation of both the packing ring and the contact surface, as shown in Figure 4 (2). Since in the assembly there is no approximate linear contact between the contact surface and the ring, even a moderate force is sufficient to cause deformation. This cannot be regarded as a clamped joint.

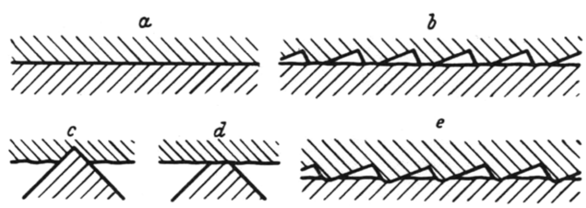


Figure 1 - Working Principles of Tight Contact Joints

a. Ideal form of sealing surfaces
b. Sealing surfaces fitted by grinding
c and d. Molded packing rings
e. Seal obtained by deformation of contact surfaces

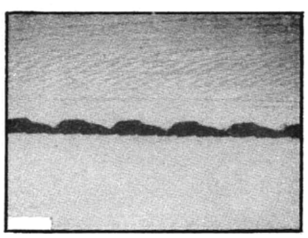


Figure 2 - Cross Section through Contact Surfaces from which too much Metal has been cut away

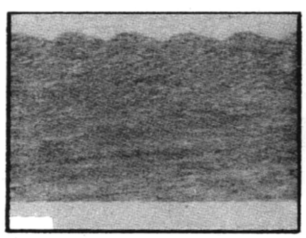


Figure 3 - Seal obtained by Filling up Surface Irregularities

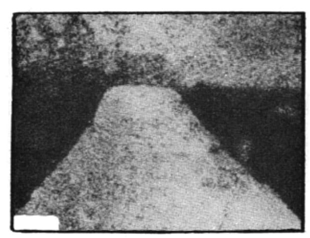


Figure 4 - Seal obtained by Molded Packing

Figure 5 shows a flanged joint. To seal this joint a force P_k is required. This is generated by means of bolts, screw caps, wedges, etc. This sealing force is the criterion for calculating the strength of the joint. It is the sum of the force acting on the contact surface, $p_d \pi (D_a^2 - D_i^2)/4$, and of the inside force, $P_i = p_i \pi D_i^2/4$,

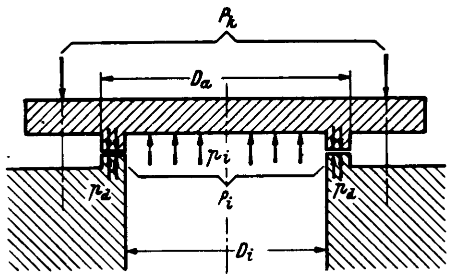


Figure 5 - Packing of a Flanged Joint

D_a and D_i outside and inside diameters of contact surfaces

p_d sealing pressure (surface pressure on packing)

p_i internal pressure

$P_i = p_i \pi \frac{D_i^2}{4}$, inside force

$P_k = P_i + p_d \pi \frac{D_a^2 - D_i^2}{4}$, sealing force

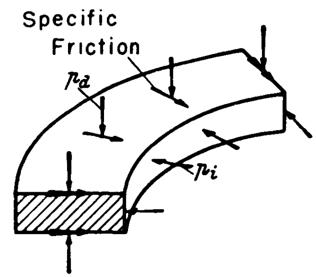


Figure 6 - Loading of a Packing Ring by the Sealing Pressure p_d, Inside Pressure p_i, and Specific Friction

where D_a and D_i are the outside and inside diameters, respectively, of the contact surfaces, p_d is the sealing pressure, and p_i is the internal pressure. The ratio of the sealing force to the internal force, P_k/P_i, is taken as the characteristic number for the joint. The smaller this ratio, the smaller the material outlay for constructing the joint.

In the case of a metal-to-metal joint or of a gasketed joint, the sealing pressure, $p_d = 4\ (P_k - P_i)/\pi(D_a^2 - D_i^2)$, is essential. The ratio p_d/p_i is important in determining the behavior of the seal. Tightness is destroyed when the packing is forced out by the internal pressure. The forces involved, Figure 6, subject the joint to normal stresses and to shear stresses. The necessary sealing pressure depends upon the internal pressure, the thickness of the packing and on the coefficient of friction between the packing and the contact surfaces. Finally the methods which entail considerable alteration in surface conformation, for instance sealing grooves machined in the flanges, are highly important. The minimum thickness of the packing is governed by the amount of plasticity required (irregularities of the surface, poorly fitted flanges, etc.).

CLAMPED JOINTS

Joints which are sealed not by working pressure but by some external force are known as clamped joints. This class includes joints with contact surfaces fitted by grinding, gasketed joints, and joints with molded packing rings.

GROUND CONTACT SURFACES

The advantages of ground surfaces are: ease of dismounting; almost exact adherence to the dimensions of the joint, since deformations are usually negligible;

mobility of the joint; no contamination of substance inside the joint by pieces of packing, and no danger of sudden disintegration. They have long been used, especially in the housings of steam turbines and in cylinder heads of reciprocating steam engines, and frequently in conjunction with a graphite-oil paste and intermediate layers of thin asbestos cord, which is compressed to a thickness of about one-tenth of a millimeter (0.004 inch). Good workmanship in smoothing the joint faces and the resulting smallness of the irregularities to be leveled off, permit the use of small thicknesses of packing. Strictly speaking, however, this joint would then no longer belong in this group. Its use is also recommended in high-pressure pipe lines (4). Its sealing force can be increased by the use of beveled contact surfaces, such as are often used in screw couplings.

Tests of the behavior of ground contact surfaces show that tightness is poor in dry joints even with high sealing pressures. Contact surfaces with a high degree of finish (mated) behave differently, but are unimportant in general machine construction. Lubricating the joint faces with grease, graphite, oil, graphite and water, and the like, improves tightness.

GASKETS

The use of sealing cements, which act as gaskets automatically shaped between the joint surfaces, falls in this category (5).

Types of gaskets are as numerous as their use is simple. Recent research papers (6) to (12) discuss the behavior of different materials in detail. The research of F. A. Raible (6) in this connection covers internal pressures up to 160 atmospheres of absolute pressure (2352 pounds per square inch) and contact-surface temperatures up to 500 degrees centigrade (932 degrees F). The flange forms used by him and the gaskets which he tested are shown in Figure 7 and Table 1, respectively.

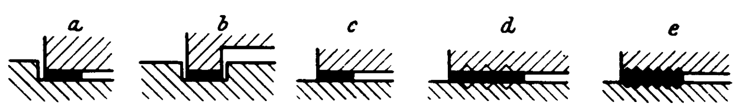


Figure 7 - Flange Types used by Raible

TABLE 1

Packings Investigated by Raible

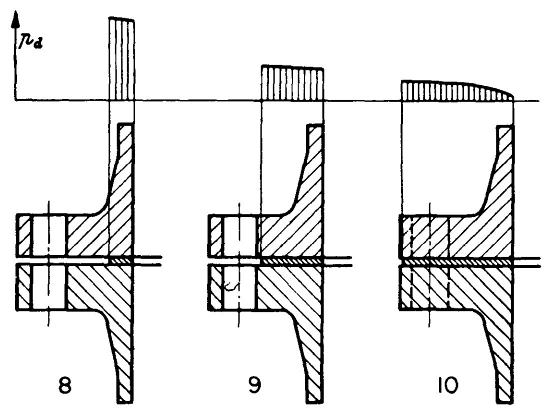
Soft Packing	Rubber, leather, fiber, asbestos, insulating materials
Hard Packing	Lead, aluminum, copper, monel metal, malleable iron, V2A*-steel
Metal and Asbestos Packing	Copper-asbestos, V2A*-steel-asbestos
*Translator's note: Believed to be a type of corrosion-resisting steel	

Soft Packing

The materials used are leather, fibre, asbestos, insulating materials, cork, rubber, and substitute materials.

Two examples will illustrate to what extent the characteristic number depends on the dimensions of the packing and on the method of installation.

For a given sealing force P_k, the sealing pressure p_d is a function of the width of the joint when the internal diameter D_i of the packing is assumed to be constant, as shown in Figure 5. Types of gasket installations, Figures 8 to 10, show the varied patterns which sealing pressures may assume. Flange stresses and strains are also varied. Assuming the sealing pressure in Figure 9 to be correct, the pressure per unit of area in Figure 8 is seen to be unnecessarily high, while in Figure 10 the tightness of the joint is doubtful. Figure 11 shows the effect of the width of the contact surface on the characteristic number of a flanged joint. A wide contact surface, with a given outside diameter, requires a high sealing force and results in a higher characteristic number.



Figures 8 to 10 - Effect of Width of Packing on the Sealing Pressure p_d

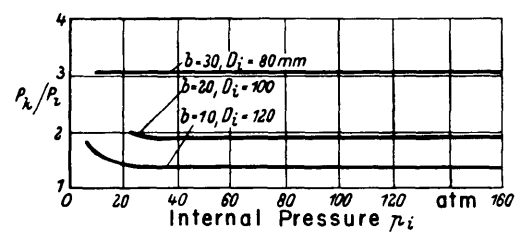


Figure 11 - Effect of Width of Packing b and Inside Pressure p_i on the Characteristic Number P_k/P_i of a Rubber Gasket

Gasket thickness 2 mm (0.0787 inches), flange Type a, Figure 7. From Raible's tests at 20 degrees centigrade (68°F)

P_i Inside force. P_k Sealing force. D_i Inside diameter of gasket

Figure 12 illustrates the importance of the method of installing gaskets. A gasket between smooth sealing surfaces, Curve c, must be strongly compressed so that it will not be forced out. Grooves, into which a plastic material is squeezed, allow a considerable reduction of sealing force, thereby improving the characteristic number. Smooth contact surfaces are possible only up to medium pressures when narrow gaskets of soft material are used, because high internal pressures would break such gaskets.

Insulating materials form an important group. They include asbestos, rubber, and admixed materials. The behavior of these materials is judged by the heat loss due to radiation, which is usually measured at 1000 degrees centigrade (1832 degrees F). Since the insulating materials cannot be used at such high temperatures because of

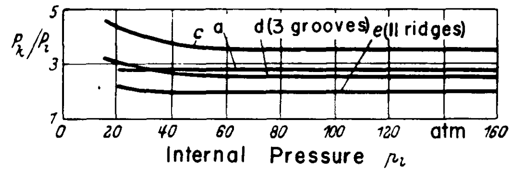


Figure 12 - Effect of Flange Shape on the Characteristic Number of an Asbestos Gasket, from Raible

Curves *a* to *e* apply to the flange shapes, Figure 7

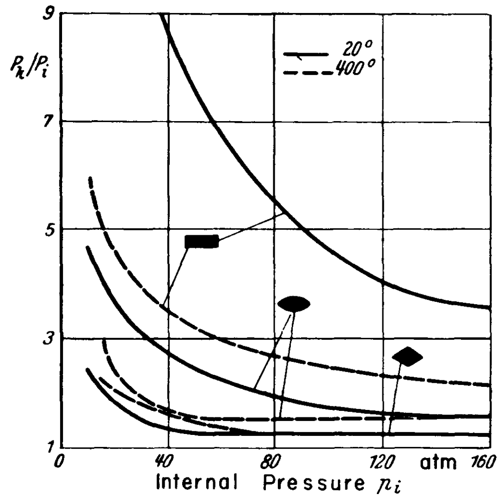


Figure 13 - Effect of Temperature on the Characteristic Number of Mild Steel Rings, from Raible

their rubber content, it would be more practical to determine the heat losses due to radiation at actual working temperatures, for example, 300, 400, and 500 degrees centigrade (572, 752, 932 degrees F). However, there are insulating materials which contain no rubber and which are useful at high temperatures. It is also possible to obtain gaskets which are resistant to various chemical actions.

Hard Packing

This group consists mainly of metal gaskets, which are made of aluminum, lead, copper, red brass, mild steel, nickel, or alloy steel, depending upon their intended use and their required resistance to corrosion and high-temperature creep strength.

Their advantage lies in their ability to withstand high pressures and temperatures. In general they are uneconomical at low pressures and temperatures, as shown by Figure 13. Hard packing is used chiefly in the form of molded rings, rather than in the form of gaskets.

Composite Packing

This group includes many possible forms. Asbestos, insulating material, leather, rubber, synthetic rubber, and other synthetics serve as the soft materials, while light metal (having a specific gravity of less than 3.0), copper, nickel, and steel are used as metal fillers.

The soft materials are used chiefly to make the joint tight; the metal part provides the necessary tenacity and supports the soft material, as shown in Figure 14a. In the case of the type shown in Figure 14b, for example, the metal rim protects the soft material from the hot gases of combustion in a cylinder head. In Figure 14c the main packing is wire-web. This packing is required to seal openings of very small cross-section. Figure 14d shows a type which is particularly flexible because the metal nowhere reaches the surface of the packing. Partial or complete metallic

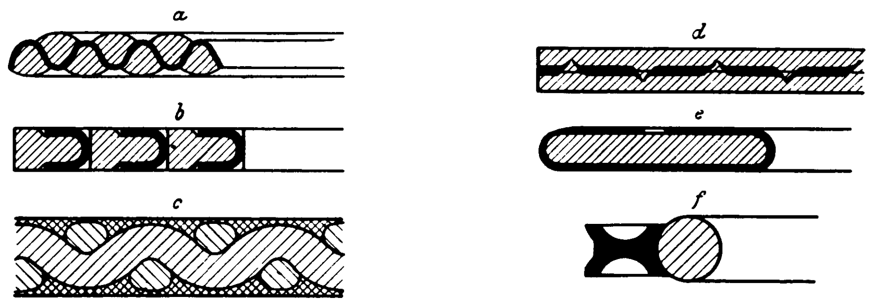


Figure 14 - Types of Composite Packing

a. Corrugated ring with soft filler

b. Ring of soft material with metal insert (Structural element of the nested packing composed of removable rings, Figure 26)

c. Wire net impregnated with packing material

d. Barbed steel core with pressed asbestos coating on both sides

e. Metal-sheathed ring of soft material

f. Rubber ring in a metal race

sheathing (Figure 14e) is preferable when the soft packing must be protected from fuel or from the action of the surroundings. In this case the metal acts as the seal, while the soft material provides elasticity. Figure 14f shows a metal supporting ring, which provides the support, and a rubber seal ring. Since the internal pressure generates an internal sealing force in addition to the external sealing force, this packing is intermediate between the clamped joints previously described and the self-sealing chambered joints.

Raible's experiments did not give a clear picture of the performance of composite gaskets. The experimental points scatter considerably. Performance was better at high temperatures than at room temperature, but the characteristic number still remained between 2 and 3.

MOLDED PACKING RINGS

These packing rings are almost exclusively metallic. Figure 13 shows the great influence of the ring cross-section on the characteristic number. When there are sharp edges on the rings, the material begins to flow and the surfaces become adjusted to each other when the sealing force is still small. In the case of the most easily deformed cross-section, the double-edged saw type, the effect of temperature is slight.

Molded rings are classified according to the shape of cross section as grooved (saw-toothed metal rings) or lens-shaped rings.

Grooved Rings

The primary type of grooved ring is that with a double-edged-saw cross-section. Grooved rings are of metal with several uniform ridges. The number of ridges is important. When there are too many ridges excessive sealing force is required since this force is distributed over many points of contact. This impairs the characteristic number of the joint, as illustrated by Figure 15. These rings are composed of either mild steel (steel with a Brinell hardness number of 90 to 120) or hard steel (alloy steel). If the joint is exposed to corrosion at low temperatures, copper, lead, or light metal may be used as composition material. If soft iron is used, the usual flange material is harder than the material composing the ridges; the deformations are therefore confined to the latter as shown in Figure 1d.

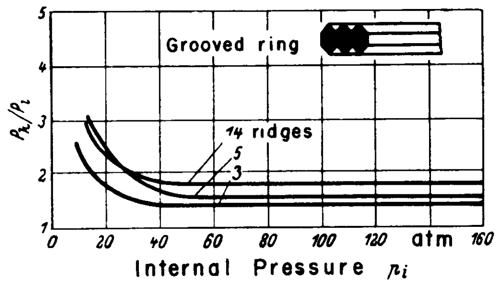
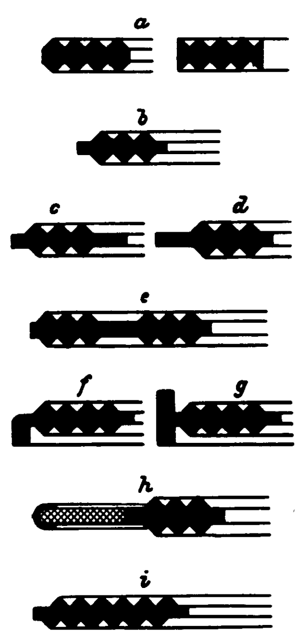


Figure 15 - Effect of the Number of Grooves on the Characteristic Number of a Grooved Ring of Mild (Armco) Steel, from Raible

Grooved rings of hard steel are used with flanges of the same material. Slight deformations then occur in the packing ring, as well as in the sealing surfaces, as shown in Figure 4. If the packing material is considerably harder than the material of the flanges, deformations will occur only in the flanges, Figure 1c. In this case it should be borne in mind that when cold shaping takes place, the shaped material will be harder. It is recommended that there be at least 5 ridges, that the space between them be from 1 to 2 millimeters (0.04 to 0.08 inch) wide, and that the packing be from 2 to 5 millimeters (0.08 to 0.20 inch) thick. Figure 16 shows cross sections of the commonest grooved metal rings. In the case of grooved rings with a sheathing of asbestos-graphite, for instance, it is important that the packing material which is used to prevent corrosion, does not, because of hardness, restrict deformation of the actual packing, which would impair the characteristic number.

Flanged joints with grooved rings require a good finish of the contact surfaces. It is advisable to make delivery in rough-ground condition and to finish the surfaces in the field. The grinding should be done concentrically with the axis of the flange, in order to avoid radial grinding grooves. The materials selected should be such as to cause the main deformation to occur in the



a. simple types
b. with impact tongues
c. with inside centering tongues
d. with outside centering tongues
e. partially ridged with impact tongue
f. with a single outside axial flanged centering tongue
g. with double outside axial centering tongues
h. with outside centering tongues of soft material
i. with offset ridges

Figure 16 - Common Grooved Metal Rings

packing. The number of grooves should be so selected that the sealing force causes penetration of a depth approximately the same as that of the surface irregularities. Consequently, the number of grooves is not determined by the width of the surfaces. Furthermore, careful workmanship is essential in grooving such rings, Figures 17 and 18 (2). The centering edge or tongue assures proper seating. There should be no danger of excessive tightening since when the ring is sufficiently thick it offers sufficient protection against overloading. Moreover, the ring will not be damaged when heat-resistant bolts in high-temperature joints are tightened.

Lenticular Rings

The lenticular ring has convex surfaces which are in contact with conical surfaces, Figure 19.

In addition to the most widely used section, Figure 19a, there are other special shapes. The ring shown in Figure 19b, which is for large forces, has a strengthening rim. That shown in 19c is convex on one side to allow movement of the connected parts due to thermal expansion normal to the axis of the cylinder.

The bellows ring, Figure 19d, is designed for cases in which large temperature variations occur in the flanges. If the temperature suddenly drops, the bolts and flanges usually retain heat much longer than the packing rings, which thus become loose. In the case of the bellows ring a part of the working pressure is used to shape the bellows and the other part to press the halves of the ring together. Thus the self-tightening idea is applied to lenticular rings, assuring protection against failure of outside pressure.

Lenticular rings have linear contact when the bolts of the joint are not tightly drawn up. In the operating condition this is changed into circular plane contact from 2 mm to a maximum of 3 mm in width, Figure 20 (2) by the elastic and plastic deformation of the ring. If the width of these pressure surfaces is materially increased by excessive drawing up of the bolts, the permanency of the seal is impaired. This is attributed to the large deformation (shrinkage) due to excessive sealing force. The ring slips

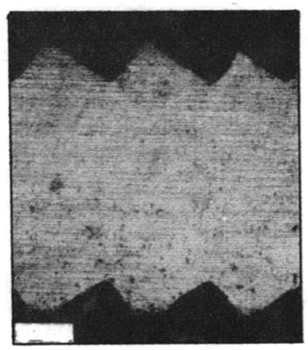


Figure 17 - Ring with Defective Grooves

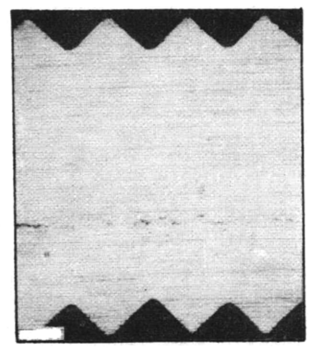


Figure 18 - Ring with Satisfactory Grooves

a. usual lens section
b. reinforced section
c. half lens section
d. bellows lens section
e. lens section, radially drilled
f. necked lens section

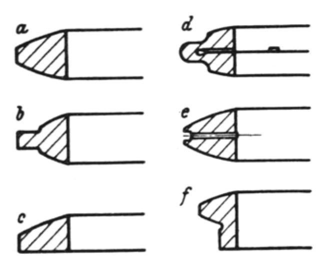


Figure 19 - Lenticular Rings

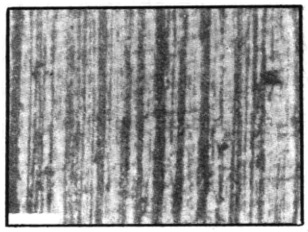


Figure 20 - Surface of a Correctly Compressed Lens Ring with Sharp Impressions of Machine Scores

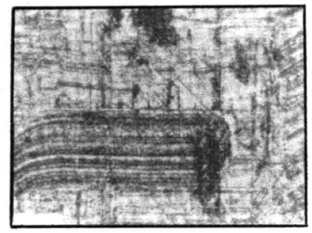


Figure 21 - Surface of a Lens Ring too Tightly Compressed with Imprints of Machine Scores Destroyed by Slip

on the joint faces, Figure 21 (2), which prevents the proper filling of the irregularities in the joint faces.

A characteristic number of 3 can be accepted for lenticular rings. One advantage is the fact that inaccuracies in the mating of the ends of pipes can be offset. However, the resultant inclined position of the flanges to each other is detrimental to the screw coupling, and must always be taken into account.

The materials are usually selected so that plastic deformation is confined to the ring. Harder materials are used when the ring is subject to a heavy load by high coupling forces. When high temperatures are involved, heat-resistant materials must be used.

Also included in the lenticular group are metal rings of circular, oval, or lens-shaped cross section, and also rings whose sealing action is accomplished by inside wedges worked directly into the flanges, or by the convex outside portion. Although the latter have good adjustability they are sensitive to repeated loosening because of the deformation of the contact surfaces. Lenticular rings in which deformation is limited to easily replaceable parts are preferable.

SELF-SEALING RINGS

RINGS IN SLOTS, STRESS-RELIEVED RINGS

In the design illustrated in Figure 22 the internal pressure forces the rubber ring into the wedge-shaped slot. The dimensions of the ring are usually such that it may be considered as a combination of a pressed ring and slotted ring. There have been many proposals to use the self-sealing method (upset ring), whose value has been proved in moving machine parts, for flanged joints also (14).

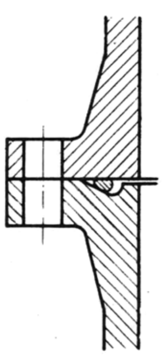


Figure 22

Self-Sealing Packing Ring

The self-sealing ring has many advantages over the joint with machined faces, without the difficulty of manufacture.

JOINTS SEALED BY WELDING

Joints sealed by welding and joints with machined contact faces are made without packing.

The welded seals, Figures 23 and 24, are distinct from the welded flange joint, Figure 25. The latter comes under the head of welded joints, because it lacks the characteristic of even limited demountability. As in sealing by means of machined contact surfaces, the pipe forces are transmitted directly from one pipe to another through the ends of the pipes, and the welded seal is entirely stress-relieved. They can be disassembled by removing the weld bead.

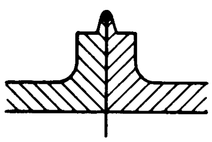


Figure 23
Straight-Lip Weld

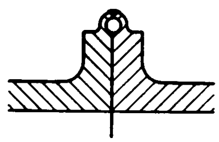


Figure 24
Round-Lip Weld

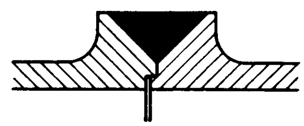


Figure 25
Welded Flange Joint

Two types of lip welding are well known. In the older straight-lip type, Figure 23, any liquid which penetrates into the unavoidable cavity under the bead, if prevented from escaping, may fracture the weld when it vaporises. In the more recent round-lip method, Figure 24, conditions are much improved. This type of seal is also recommended for screw joints. Dangerous pressure increases in the cavity of the weld can be avoided by drilling pressure-relieving openings.

THE DESIGN OF FLANGED JOINTS

Based on the tests here discussed, the characteristic number P_k/P_i can be accepted for a flanged joint, and from it the sealing force can be determined. With non-metallic packing at pressures greater than 10 atmospheres (142 pounds per square inch) the characteristic number obtained will always be less than 2. Metal gaskets usually yield higher characteristic numbers. Their advantages become apparent only at higher internal pressures ($p_i > 50$ atmospheres) but they then have a characteristic number of less than 3. Molded metal rings are even more advantageous and likewise have a characteristic number of up to 2. Often, particularly for large flange diameters, it is advisable to use the ratio of the specific coupling pressures, p_d/p_i, as a criterion instead of the characteristic number. For this the following values are given:

For gaskets between guide facings $p_d/p_i = 2$ to 4

For wide slot-and-feather rings $p_d/p_i = 3$ to 6

For narrow slot-and-feather rings $p_d/p_i = 3$ to 8

The width of the gasket is taken as 5 to 10 per cent of the inside diameter.

For flanged pipe couplings reference is again made to the DIN sheets on this subject (16).

To permit use of the foregoing values a flanged joint must be very rigidly connected. Any deformation of the flanges affects the tightness of the joint unfavorably. In difficult cases the flanges and bolts must be calculated as accurately as possible (15)(17). With large flanged joints it is also possible to avoid deformations to a large extent by proper design (18). Moreover, correct assembly is highly important. It is futile for the designer to specify a certain bolt pressure if the mechanic draws the bolts up to suit himself. Various methods of checking bolt stresses have been proposed (19). Flanged joints whose design had been based purely on theory have not stood up in the long run. The reason for this is the "setting" of all the surfaces of a flanged joint under protracted pressure (13). By this is meant the gradual diminution of roughness of the surfaces under compression, as well as the plastic deformation of non-heat-resistant parts. Therefore it is necessary at first to apply an excess of bolt pressure, which will then be taken up by the setting. At high working temperatures the flanged joint must be carefully guarded from overstress due to thermal expansion. This is done by means of expansion bolts, springs, and shims of low-temperature steel capable of plastic deformation. These measures also prevent loss of sealing force in the packing. When the type of flanged joint is known, the maximum permissible characteristic number is also known and the packing can be selected accordingly. Nested ring packing, Figure 26 (2)* permits the characteristic number to be determined later because the characteristic number P_k/P_i is changed by the removal of individual rings, Figure 27.**

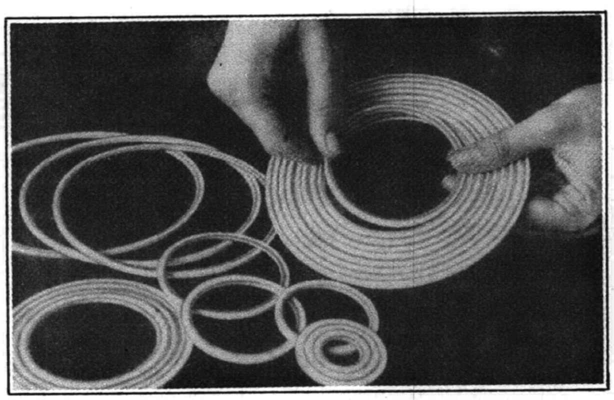


Figure 26 - Nested-Ring Packing Consisting of Separate Rings, Figure 14b

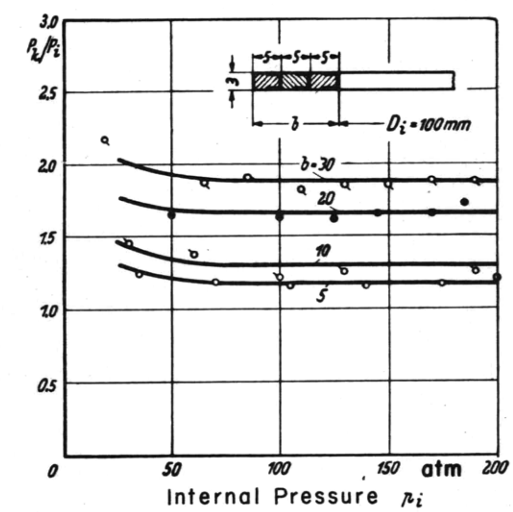


Figure 27 - Characteristic Number of Nested-Ring Packing as a Function of the Number of Rings

* German Patent 686556

** Tests at the Goetzewerk, Burscheid b. Köln

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