EXPANDED TUBE JOINTS IN BOILERS

by

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From the earliest days of water-tube boilers the practice of expanding the tubes into the drums or headers has been adopted as the most convenient method of making a satisfactory joint. Until recently very little thought or scientific research had been applied to this important part of boiler construction, but with the use of higher steam pressures and temperatures it has become increasingly necessary to investigate the problem and determine the conditions which must be fulfilled to make a satisfactory joint.

The object of this article is to explain in very general terms the mechanism of expanding, to examine the various factors which go to make a satisfactory joint under working conditions, and thus to point out the possible limitations of expanded tube joints for future developments.

No attempt has been made to give the theoretical analysis on which some of the statements and calculations have been based, and throughout the article it is assumed that an expanding tool of the normal design fitted with 3 rollers and a tapered mandrel will be used for rolling the joint.

The Mechanism of Rolling

Let us first consider very briefly what happens when a tube is rolled into a tube plate.

The action of the expanding tool forces the rollers outwards against the surface of the tube creating a radial pressure sufficiently high to yield the tube material. As the rolling continues the yield spreads outwards through the tube until at the finish of the expanding operation the whole of the tube, and usually a portion of the tube plate adjacent to the hole, has become plastic. This plastic zone around the hole is backed by a large volume of elastically deformed material which is ready to spring back when the rolling pressure is released. The theoretical stress distribution at the end of the rolling operation in a typical case is shown in Fig. 1.

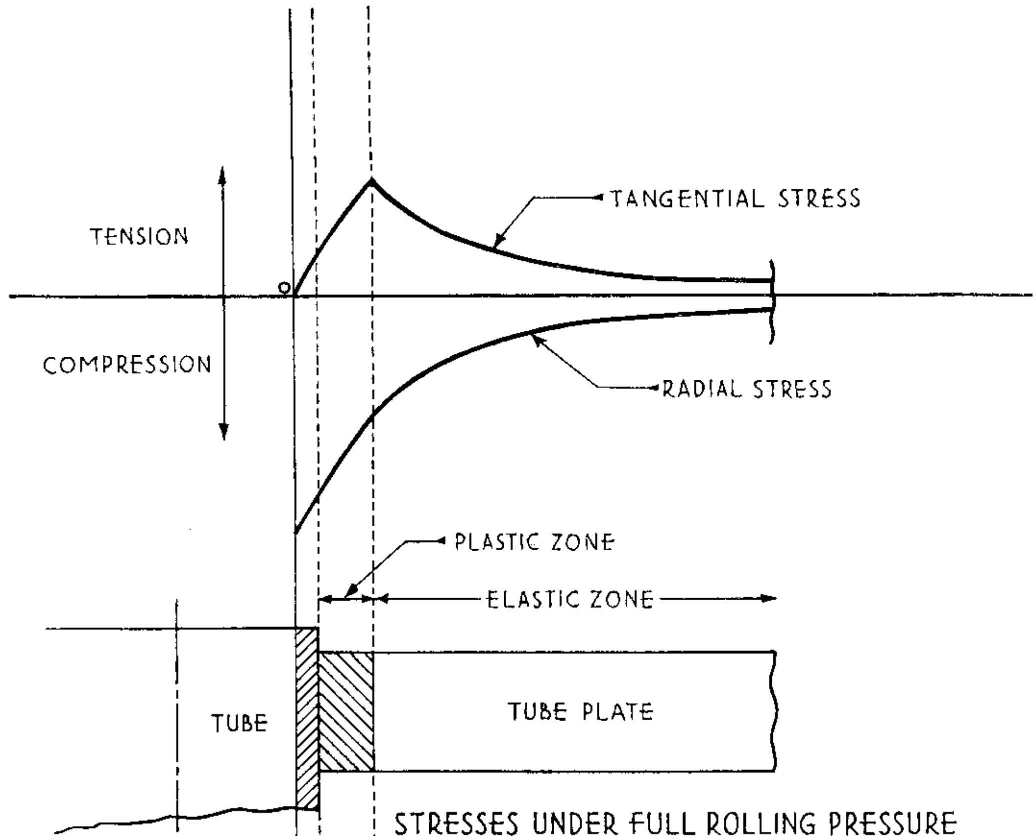
When the expander is withdrawn the elastic material of the tube plate contracts and grips the plastically deformed tube so that a residual pressure remains between the outside of the tube and the tube plate.

It is this residual pressure, known as the contact pressure, which prevents leakage and gives structural strength to the joint. Fig. 2 shows the theoretical residual stresses left in a typical joint after the expander has been withdrawn.

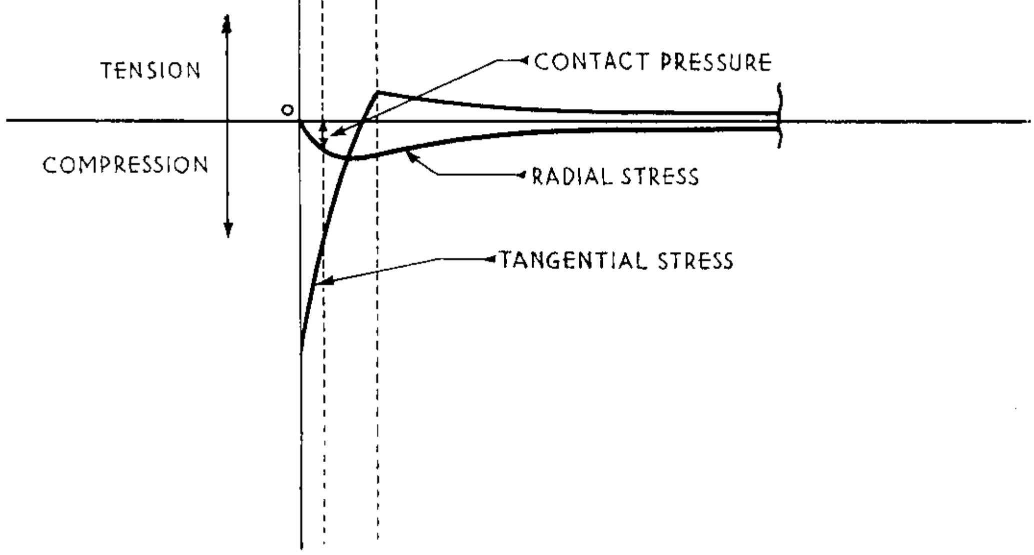
It should perhaps be stressed here that an expanded joint has two quite separate functions to fulfil :—

(i) It must be tight against leakage.

(ii) It must have the necessary structural strength to support the weight of the boiler steam-drum, etc., and to resist the strains due to temperature differences and movements of the ship.



STRESSES UNDER FULL ROLLING PRESSURE
FIG. 1.



RESIDUAL STRESSES ON COMPLETION OF ROLLING
FIG. 2

To fulfil condition (i) the contact pressure should be at least equal to, and preferably slightly in excess of, the drum pressure. The fulfilment of condition (ii) depends not only on the contact pressure, but also on the coefficient of friction between the tube and tube plate after expanding. In normal boiler designs if condition (i) is satisfied there will usually be a large factor of safety in the structural strength of the joint.

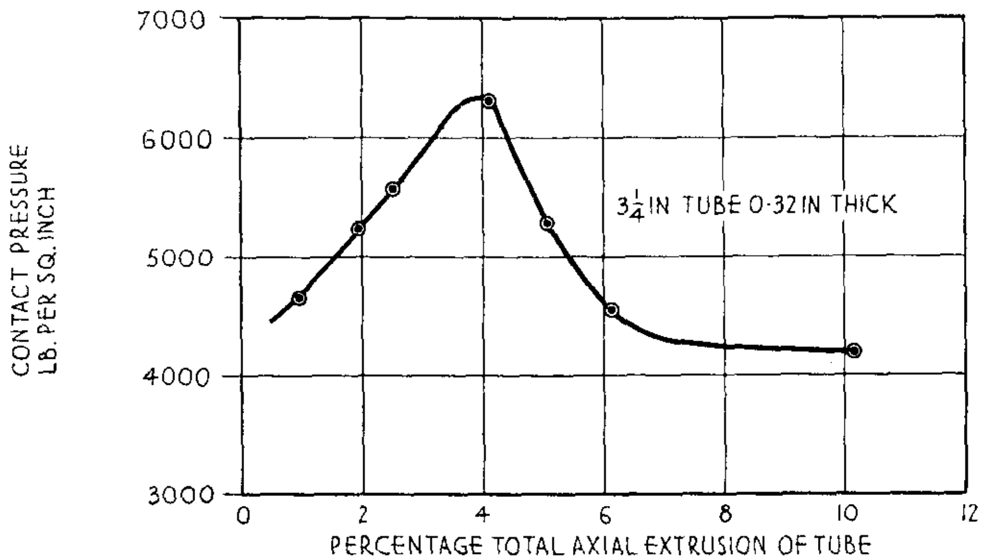


FIG. 3

Variation in the Contact Pressure with the Amount of Rolling

One of the most important factors in the making of an expanded tube joint is to know exactly how far to continue the rolling in order to obtain the best results. Fortunately there is plenty of experimental data on this point and Fig. 3 is a typical curve, taken from the results of Grimison and Lee in America, showing the variation in contact pressure with the amount of rolling for a $3\frac{1}{4}$ in tube 0.32 in thick. In this case the amount of rolling was measured by the total elongation of the tube. It will be seen that the contact pressure at first rises with the increase in the amount of rolling but soon reaches a sharply peaked maximum. Further rolling then causes the contact pressure to decrease until a more or less constant value is reached.

It is now a well-established fact that for any particular joint there is a very definite maximum value of contact pressure which cannot be exceeded, and to obtain this maximum the amount of rolling must be controlled within narrow limits.

Much controversy has centred round the sudden drop in contact pressure with increasing rolling, but generally speaking the accepted explanation is as follows :—

At the beginning of the expanding operation the axial lengthening of the tube is resisted by the friction between the tube and tube plate. As the rolling is progressed the material becomes plastic and the friction between the two surfaces is decreased until the tube slips and the resistance to axial extrusion is destroyed. The pressure on the rollers then drops rapidly, and further rolling merely causes continued axial extrusion of the tube without any appreciable increase in rolling pressure.

Now the residual contact pressure in the joint after expanding depends upon the rolling pressure, so that the value of the contact pressure will rise to a maximum and then fall off again as the amount of rolling is increased.

The maximum value of contact pressure is obtained just before slipping occurs between the tube and tube plate.

Effect of Grooves and Rough Surfaces in increasing the Contact Pressure

It will be seen that if the easy axial extrusion of the tube can be prevented during rolling the contact pressure should be increased. Attempts have been made to do this by increasing the roughness of the tube and hole surfaces, and by machining grooves in the tube holes.

In practice it has been found that a slight increase in the roughness of the surfaces increases the contact pressure but if this is carried too far there is considerable difficulty in making a tight joint.

The machining of grooves in the tube holes may increase the maximum contact pressure by as much as 50% in some cases. In one series of tests it was found that the best results were obtained with two grooves about $\frac{3}{32}$ in wide, $\frac{1}{32}$ in deep, and separated $\frac{7}{16}$ in on centres, located in the centre of a tube plate $1\frac{1}{4}$ in to $1\frac{1}{2}$ in thick.

Control of the Expanding Operation in Practice

The amount of rolling given to a joint is extremely important if the best results are to be obtained. Excessive rolling not only reduces the contact pressure but increases the likelihood of corrosion and caustic embrittlement, and every effort should be made to reduce the cold working of the material to a minimum. In this connection it should be noted that too large a clearance between tube and hole may lead to excessive cold working of the tube end if the joint is to be expanded to give the maximum contact pressure.

In boilers where the working pressure is comparatively low the amount of rolling can be safely left to the experience of the boiler-maker. He expands the tube until it 'feels right' and then if it leaks under test he expands it a little more.

In high pressure boilers, however, a more exact degree of expansion must be achieved if leakage is to be avoided, and the practical problem of ensuring that all the joints in a boiler are given the correct amount of expansion corresponding to the maximum contact pressure can be conveniently divided into two sections :—

(i) The determination of the correct amount of rolling for the particular joint.

(ii) The control of the rolling operation so that all the joints are expanded to the correct amount as determined in (i).

Determination of the Correct amount of Rolling

The most satisfactory method is to carry out a series of tests under the actual conditions that will obtain in practice.

Some lengths of the actual tubing should be expanded into holes cut in a dummy tube plate, with gradually increasing amounts of rolling as indicated by one of the methods given in next section. The dummy plate should be of the same material and have the same thickness and hole spacing as the boiler-drum, and the method of expanding should be identical with that to be used on the actual boiler.

After each rolling operation the tube should be cut out and the inside surface of the tube hole carefully examined. As soon as definite signs of slipping are visible it can be assumed that the rolling of that particular tube has been carried too far. The correct amount of rolling occurs just before any signs of slipping are visible on the inside of the tube hole.

Alternatively the maximum force that can be applied to the tube end before the joint slips may be used as a measure of the correct amount of rolling.

Control of Rolling

Several methods have been suggested for measuring the amount of rolling given to the tubes to ensure that they will all be correctly expanded. Among the most important are :—

(i) Gauging the internal diameter of the expanded tube.

(ii) Measuring the elongation (or axial extrusion) of the tube when expanding by an extensometer.

(iii) Gauging the external diameter of the expanded tube adjacent to the tube plate on the gas side.

(iv) Measuring the axial travel of the mandrel.

(v) Checking the number of mandrel turns or the number of cage turns.

(vi) Checking the mandrel torque or the power input to the mandrel (for power operated expanders).

The accuracy of the first three methods depends on keeping the tolerances of the tubes and tube holes within fine limits. There should be no difficulty in this as far as the tube hole is concerned but with drawn tubes it is unlikely that the tube tolerances will be fine enough to ensure accurate results with method (i).

Method (ii) is considered by many experts to give the most consistent results but is difficult to apply under practical conditions. Probably the simplest procedure is a form of method (vi) where an electrically-driven expander fitted with an automatic cut-out stops the expanding when the current reaches a pre-determined value. This method can give consistent results provided the overall coefficient of friction from the outside of the rollers through to the driving spindle remains constant.

The correct amount of rolling for any joint will vary with the properties and sizes of the tube and tube plate and with many other factors, but the following figures are intended to give a rough indication of the measurements in the methods (i), (ii) and (iii) which will correspond to the optimum degree of expanding :—

(i) Increase in the internal diameter of the tube during expanding—from 1% to $3\frac{1}{2}\%$.

(ii) Total axial extrusion of the tube (both sides) during expanding—from 3% to 8%.

(iii) Increase in the external diameter of the tube during expanding—from $\frac{1}{2}\%$ to $1\frac{3}{4}\%$.

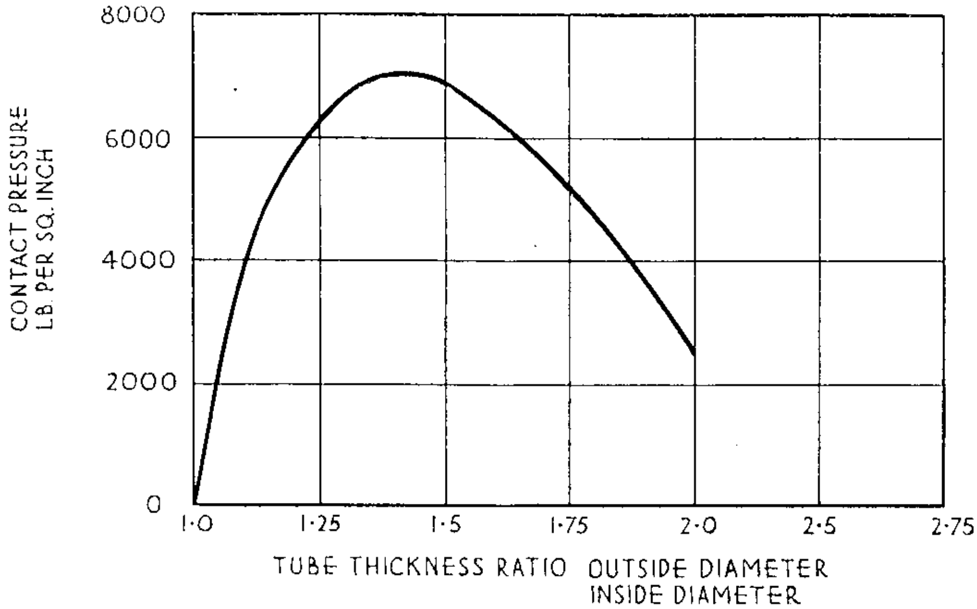


FIG. 4

All the measurements are taken from the point where the tube is first nipped in the tube plate.

Whatever methods are used the rolling operation should never be carried out too quickly, otherwise the temperature of the tube may rise considerably above that of the drum material, and relaxation of the contact pressure will occur on cooling.

Other factors affecting the Contact Pressure

It has been stated above that there is a definite maximum value of contact pressure associated with any given joint ; this maximum value is affected by variations in the sizes and materials of the tube and tube plate.

Tube Thickness

Fig. 4 shows the effect of the tube thickness on the maximum value of contact pressure. This curve has been plotted from an equation developed theoretically, and the values of contact pressure have been worked out for identical drum and tube materials with a yield strength of 40,000 lb/sq. in. It will be seen that the contact pressure is independent of the actual size of the tube, and depends only on the ratio of outside to inside diameter. The contact pressure rises with increase in tube thickness until a diameter ratio of about 1.4 is reached and from this point onwards it decreases again.

Experimental values of contact pressures with various tube diameter ratios up to a value of 1.45 are in good agreement with the theoretical curve, but unfortunately there are no results available with thicker tubes to confirm the drop in contact pressure predicted above this value.

However, with the normal tube sizes met with in the Service (diameter ratio less than 1.4) the maximum contact pressure increases with increase in tube wall thickness.

Mechanical Properties of the Tube and Drum

The most important properties of the tube or drum as far as expanding is concerned are the yield strength, since this controls the pressure at which plastic flow begins, and the strain hardening qualities. The hardness value of a material is an indirect measurement of these two properties, and thus it is usual to compare the expanding qualities of various materials in terms of their hardness value.

Experimental evidence shows that increase in the hardness of either tube or the tube plate increases the contact pressure up to a certain point. When the difference in hardness has reached a limiting value, of the order of 150 Brinell Number, further increase produces no appreciable effect on the contact pressure. From the practical point of view, however, it has been found difficult to obtain satisfactory joints if the hardness of the tube is considerably greater than that of the plate.

The most satisfactory combination appears to be with a tube plate hardness of between 10 and 20 Brinell Number in excess of the tube hardness.

Tube Plate Thickness

The thickness of the tube plate has an influence both on the strength of the joint as a whole and on the contact pressure.

Assuming that the contact pressure remains the same, the increased area of contact due to a thicker tube plate will give a stronger joint, but, in addition, the thicker tube-plate offers increased resistance to axial extrusion when rolling, and this results in a slightly higher value of contact pressure. After a certain thickness of plate has been reached, however, this effect is offset by the difficulty of ensuring even expanding along the whole length of the joint.

Although there is very little data available it would appear that with normal expanding tools the optimum thickness of tube plate lies somewhere between $1\frac{1}{8}$ in and $1\frac{7}{8}$ in.

The Effect of Working Conditions on the Expanded Joints in Boilers

The contact pressure remaining in an expanded tube joint will be considerably modified when the boiler is steaming. In this section we will examine the specific case of a $1\frac{3}{4}$ in fire-row tube in an Admiralty three-drum boiler with a pressure of 400 lb/sq. in., and investigate the changes that occur in the contact pressure under normal working conditions.

Assuming that the yield stress of the tube material is 40,000 lb/sq. in., theoretical calculations show that with average care in expanding it should be possible to obtain a contact pressure of about 5,200 lb/sq. in. in the joint after rolling. This value, which has been obtained from the same theoretical analysis as Fig. 4, assumes a tube thickness of 0.128 in corresponding to a diameter ratio of 1.171.

Effect of the Working Pressure

The pressure of 400 lb/sq. in. inside the tube causes it to expand outwards against the drum thus increasing the contact pressure. In this particular case the calculated increase is 300 lb/sq. in.

The effect of the pressure inside the drum, however, is a much more complex problem. The drum expands and causes the tube holes to stretch, but to a greater extent in the circumferential than in the axial direction, so that the holes not only become larger but also elliptical in shape. In actual tests it has been found that this stretch is 3 or 4 times more in the circumferential than in the axial direction, and that the general strain of the drum is magnified considerably at the tube hole due to the stress concentration there. The problem is further complicated by the fact that the tube resists the tendency of the hole to become elliptical.

The overall effect of the tube hole enlargement will be to reduce the contact pressure, but to a greater extent in the circumferential than the axial direction.

By making certain simplifying assumptions it is possible to calculate the maximum reduction in contact pressure (in the circumferential direction) and for the example considered this works out to be 2,400 lb/sq. in.

Thus the net effect of the working pressure alone is to reduce the contact pressure to a value given by :—

$$5{,}200 + 300 - 2{,}400 = 3{,}100 \text{ lb/sq. in.}$$

Effect of the Working Temperature

The uniform increase of temperature of the joint under working conditions to a value of, say, 450°F. reduces the modulus of elasticity (E) of the tube and drum material by about 7%. This has two separate effects :—

(i) The original contact pressure in the joint will be reduced in the same ratio as ' E,' *i.e.*, from 5,200 lb/sq. in to 4,800 lb/sq. in. This follows at once from Hookes' Law since the contact pressure is the direct result of the strain remaining in the joint after rolling.

(ii) The stretch of the tube hole under working conditions mentioned in the preceding section will be increased by the same amount as the change in the value of ' E.' This will have the effect of reducing the contact pressure from this cause still further, by 2,600 lb/sq. in. instead of 2,400 lb/sq. in.

Combined Effect of Pressure and Temperature

The combined effect of the working pressure and temperature will thus be to reduce the contact pressure to a value given by :—

$$4{,}800 + 300 - 2{,}600 = 2{,}500 \text{ lb/sq. in.}$$

The contact pressure necessary to prevent leakage depends to some extent upon the surface conditions of the tube and hole, but to be on the safe side it should always be slightly in excess of the drum pressure, say 500 lb/sq. in. in the example chosen. The joint considered should thus have a large factor of safety against leakage under working conditions if the expanding has been properly carried out.

It will be seen that by far the largest factor in the reduction of contact pressure under working conditions is the stretch of the tube hole. This stretch is roughly proportional to the nominal hoop stress in the drum, and therefore if any advance in boiler drum stresses is contemplated, with the introduction of alloy-steel drums for instance, the effect on the expanded tube joints must be carefully considered.

The Effect of Temperature Differences between the Tube End and the Drum

Under normal working conditions the temperature difference across the expanded joints in a well-designed boiler should be very small.

However, under special circumstances, such as overheating of the generator tubes or cooling of the superheater tubes due to priming, it is possible for considerable temperature differences to exist. This affects the expanded joints, and two cases can arise :—

Tube End Temperature greater than Drum Temperature

Where the tube end temperature is greater than the drum temperature the tube end attempts to expand against the restraining influence of the drum and thus increases the very high compressive stress remaining in the tube after rolling (see Fig. 2). While the temperature difference exists the contact pressure will be increased and, provided the tube end does not yield, it will return to its original value when the temperatures are again even. If the tube end has yielded due to the overheating then, when the temperature of the joint becomes uniform again, the contact pressure will be permanently reduced and can only be restored to its original value by re-rolling.

Tube end Temperature lower than Drum Temperature

Where the tube end temperature is lower than the drum temperature the tube contracts relative to the drum and the contact pressure is reduced while the temperature difference exists. When the temperatures are again even the contact pressure returns to its original value, and provided no leakage has occurred, the joint should not be damaged in any way.

Limitations of Expanded Tube Joints at High Working Temperatures

In the previous sections it has been assumed that the working temperature of the joint was below the creep range of the materials employed. Under these conditions the contact pressure remaining after rolling will continue to exist indefinitely while the boiler is in service, but if the working temperature is sufficiently high the effect of creep will cause a continual relaxation of the contact pressure while the boiler is steaming.

The rate at which stress relaxation occurs in a given material depends upon both the stress and the temperature, and in an expanded joint where the level of stress is different at every point, the estimation of the rate of relaxation would be extremely complex. However, the effect of creep sets a definite upper limit to the temperature at which expanded joints can be used, and with working temperatures of 900°F. to 1,000°F., such as occur in many power station superheaters, the relaxation of the residual contact pressure due to creep may be so rapid as to render an expanded joint practically useless. Under these conditions it is necessary to resort to special materials, welding, or some other construction in order to make a satisfactory joint.

It will be appreciated that this limitation due to creep can only occur in superheaters, since the temperature of the expanded joints in steam and water drums should not appreciably exceed the saturation temperature corresponding to the working pressure.

Considerations affecting the re-tubing of Boilers

Whenever a tube is expanded into a drum the material around the tube hole will be yielded and cold worked to some extent. The actual amount of the cold working will depend on the relative hardness of the tube and the drum material, and on the amount of rolling given to the joint. This cold working of the tube plate increases the likelihood of failure due to embrittlement or corrosion, and puts a limit on the number of re-tubings which can be safely tolerated without risk of cracks developing adjacent to the tube holes.

Conclusion

It has been found that in order to produce the best results, grooves should be cut in the tube holes and the expanding operation should be systematically controlled so that all tubes are given the optimum amount of rolling. It has also been discovered that the tube hole stretch has a marked effect in reducing the contact pressure under working conditions, and to counteract this the designed drum stress should be kept as low as possible.

If these conditions are fulfilled expanding is still the most practical and economic method of making the tube joints in steam and water drums for pressures as high as 2,000 lb/sq. in.

For superheaters the relaxation of the residual stresses due to creep is the limiting factor and it is doubtful if expanded tube joints can be usefully employed for steam temperatures in excess of 1,000°F.