THEORETICAL ANALYSIS OF ROLLED JOINTS

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I INTRODUCTION

Rolled joints or expanded joints are commonly used in nuclear reactors because of their ability to join dissimilar metals. The strength of such joints is strongly dependent on the residual contact pressure between the tube and the hub. In case of tube to tube joints, the hub could be sufficiently thin, requiring a suitable clamp over the hub during rolling. In case of very thin tubes, a backing ring on the inside, known as insert, is also necessary. A joint having all these features may be called restrained sandwich joint. Most of the other types of rolled joints can be treated by considering them as special cases of this joint. A theoretical analysis has been developed to deal with the analysis of a restrained sandwich type joint. The object is to determine the residual contact pressures and displacements after a given degree of rolling. Such analysis enables optimisation of major rolled joint parameters and is likely to result in significant savings in cost and time of development of rolled joints, particularly when a large number of joints are to be simultaneously developed.

II ASSUMPTIONS

The basic assumptions are as follows -

(i) The effect of grooves in the hub is not taken into account. The joint configuration of theoretical model will be as shown in fig. 1.

(2) Joint expansion is assumed to be carried out by application of a gradually increasing uniform internal hydrostatic pressure.

(3) Plane stress condition is applicable for all joint components.

(4) The external clamping pressure is assumed to be uniform over the hub outer circumference. The magnitude of this pressure is assumed to be a linear function of the radial displacement at hub outer radius.

(5) For tube and insert in plastic state Levy-Mises plastic stress-strain equations and, for hub Reuss equations, are valid.

(6) Variation of instantaneous yield stress across the wall of tube and insert is neglected. In this respect these components are treated as thin cylinders.

(7) All joint materials obey von-Mises yield criterion.

III FORMULATION OF THE PROBLEM

Due to limitation of space the formulation of the problem is being restricted to a brief description without equations. A set of equations interconnecting various variables involved during rolling is first assembled for cases of a fully elastic cylinder, partially plastic cylinder, and fully plastic cylinder. The hub is treated as a restrained thick cylinder under internal pressure while the tube and the insert are treated as thin cylinders subjected to external as well as internal pressures.

To find contact pressures and displacements at the time of rolling, we proceed as follows -

(1) Using thick cylinder equations with hub data, the values of different hub variables, (e.g., displacements, contact pressures, extent of plasticity, etc.) for gradually increasing values of hub internal radial displacement (u_b), are found. Let the functional relationship (hypothetical) between u_b and hub internal pressure (p_b) be expressed as -

$$p_b = \phi_H(u_b) \qquad \text{.........(1)}$$

(2) Using thin cylinder equations for tube with external pressure equal to zero, the values of different tube variables for gradually increasing values of tube internal radial displacement (u_a) are determined for expansion of tube in clearance gap. After the clearance gap is taken up thin cylinder equations, together with (1) are solved to find out values of different tube and hub variables at each stage of expansion. Let the hypothetical functional relationship between u_a and tube internal pressure (p_a) be expressed as -

$$p_a = \phi_T(u_a) \qquad \text{.........(2)}$$

(3) Thin cylinder equations for insert, along with (2) are then used to provide the complete solution for insert -tube-hub assembly at the time of expanding.

After attaining the required degree of expansion expanding pressure and clamp are removed. This causes elastic relaxation of all joint components. The six elastic state pressure-displacement relations for the internal and external radial displacements of the three joint components can now be solved to give the values of elastic relaxations in two unknown contact pressures and four unknown displacements. Thus the joint can be analysed for various values of nip*.

IV COMPUTER PROGRAM 'ROLLER'

The above given method of solution forms the outline of a computer program 'ROLLER'. This program can be used for restrained as well as unrestrained and sandwich as well as non-sandwich rolled joints. By taking instantaneous values of insert and tube dimensions at each stage of rolling the effect of reduction in insert and tube wall thicknesses is accounted for.

V RESULTS AND DISCUSSION

1) Comparison of Analytical Results with Grimison and Lee Experimental Data

The cases of joints experimentally investigated by Grimison and Lee /1/ were analysed with ROLLER. Since data regarding strain hardening behaviour of materials used was not available, calculations were done taking both tube and plate materials to be non-strain hardening in one case and in another case both the materials were assumed to have a strain hardening exponent value of 0.05. The results are given in Table 1.

In cases 1,2 and 3 the maximum contact pressure is reached when plastic front radius/bore radius ratio becomes equal to 1.864 for non-strain hardening and 2.440 for strain

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*Nip is a measure of degree of expansion defined as -
Nip = Final expanded insert internal diameter - (hub internal diameter -2 x Sum of tube and insert [illegible] wall thicknesses)

hardening case. Nadai [2] and Goodier and Schoessow [3] in their analyses for non-strain hardening infinite plate predicted this limit to be 1.75. The difference in our case is primarily due to different plasticity equations used for hub analysis, and secondly due to the fact that for computer calculations finite value of hub o.d. (800 mm.) was used.

TABLE - 1

Comparison of Analytical Results with Grimison and Lee Experimental Data for 3.25 inch C.I. Tubes

Case No.	Tube wall Thickness (in)	Tube Yield stress (psi)	Plate yield stress (psi)	Maximum Residual Contact Pressure (psi)			Maximum Value of Plastic Front Radius . Bore Radius Ratio	
				Experimental Value	Computed Value			
					No strain Hard.	Strain Hard.	No strain Hard.	Strain Hard.
1	0.17	53,500	31,500	5,750	3,120	5,910	1.864	2.440
2	0.32	40,000	31,500	8,100	7,910	9,400	1.864	2.440
3	0.32	40,750	28,500	6,500	5,900	7,130	1.864	2.440
4	0.50	37,800	31,500	10,450	10,800	12,500	1.553	1.852
5	0.32	40,000	13,600*	8,300	9,260	10,360	1.000	1.000

*Assumed.

In cases 4 and 5, the increase in residual contact pressure ceases before plastic front radius reaches its limiting value becuase of large plastic flow of tube which takes place after the internal pressure reaches a maximum value of 1.155 times the instantaneous value of tube yield stress.

In all the cases strain hardening is found to increase the magnitude of maximum contact pressure. Except in case 1, the values of maximum contact pressure for non-strain hardening case are found to be fairly close to the experimental values.

ii) Effect of Various Joint Parameters on Residual Contact Pressure for a Restrained Sandwich Rolled Joint.

To illustrate the effect of different joint parameters on residual contact pressure the case of a restrained sandwich rolled joint, somewhat similar to one occuring in B-5 reactor design, is taken up. The dimensions and material properties of the reference joint are given in the table given along with Fig. 1. From these values the values of different parameters are varied, one at time, to study their effect. The values of residual contact pressure at tube-hub interface have been plotted against nip in each case.

(a) Clamp Outer Diameter (Fig. 2A)

It is found that as clamp size is increased the peak of contact pressure vs. nip curve comes down. For low values of nip, we have contact pressures increasing with nip, as is to be expected. At higher nip values, however, due to large plastic flow of insert the contact pressure is limited. This plastic flow apparently occurs earlier with thicker clamps. After the peak is reached, the reduction in contact pressure is due to wall thinning as well as further strain-hardening of insert and tube.

(b) Insert Wall Thickness (Fig. 2B)

For varying insert wall thickness from its reference value i.d. of insert was maintained constant and o.d. of insert changed for different cases. The tube i.d., tube o.d., and hub i.d.

were also changed by corresponding amounts to maintain same value of tube wall thickness and tube-to-bore clearance. The curves show that a thicker insert is capable of providing a greater residual contact pressure for a given nip. The gain obtained, however, becomes smaller as the thickness is increased. The nip values required for maximum residual contact pressure are found to increase with increase in insert wall thickness.

(c) Tube and Hub Yield Stresses (Fig. 2C)

As the yield stress of tube increases, the contact pressure comes down. The effect of hub yield stress on maximum contact pressure is quite prominent; the latter increasing by more than 125 % for only 14.3 % increase in hub yield stress. This is understandable for our case where because of the small hub thickness, major limiting factor for contact pressure is the hub yield stress. These results are in agreement with past experience for ordinary non-sandwich joints [1,3].

(d) Insert Strain-hardening Exponent (Fig. 2D)

With increase in strain-hardening exponent value for insert the value of contact pressure for given nip is observed to decrease quite rapidly. Since clearance gap plays a major part in strain hardening of insert and tube it is expected that if clearance gap is reduced the contact pressure values will improve.

VI CONCLUSION

The theory presented in the paper takes into account almost all factors that can be accomodated in an analytical model. Because of its inadaptability for analytical treatment the effect of grooves could not be taken into account. Further, because of the hydrostatic pressure expansion assumption, a difference in computed and actual values of different parameters for a given degree of rolling is expected. In actual rolling process the large local deformation under the rollers adds significantly to measured nip value but does not produce a correspondingly large straining of hub. With our analytical model, the straining of hub with increase in nip will be comparatively more rapid. In certain cases analysed with ROLLER it was found that hub became significantly plastic even for moderate values of nip.

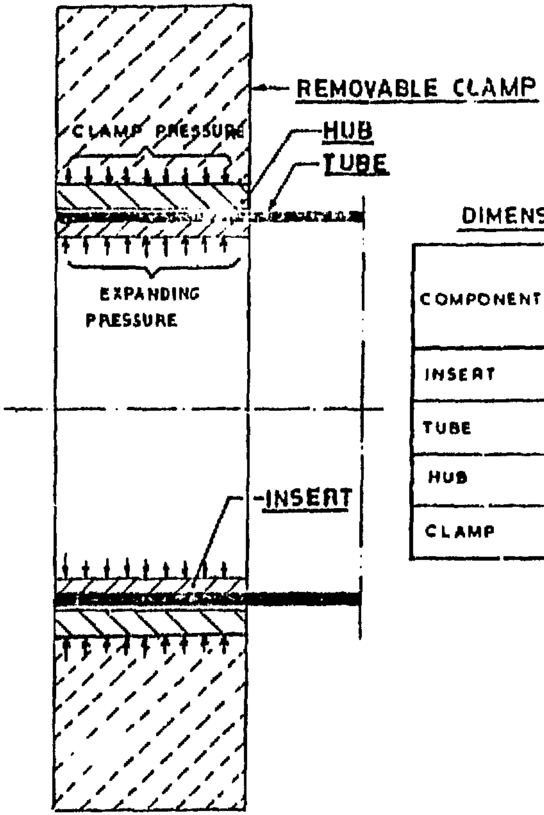
Because of the above mentioned limitations the absolute values of the different variables computed analytically may not be quite useful. However, for a comparative study of various joint designs, which normally requires lot of experimental testing, this theory is expected to be quite helpful.

It is felt that the effect of grooves and the effect of actual rolling process can be taken into account by introducing certain empirical elements in the theory. An attempt is being made to do so.

VII REFERENCES

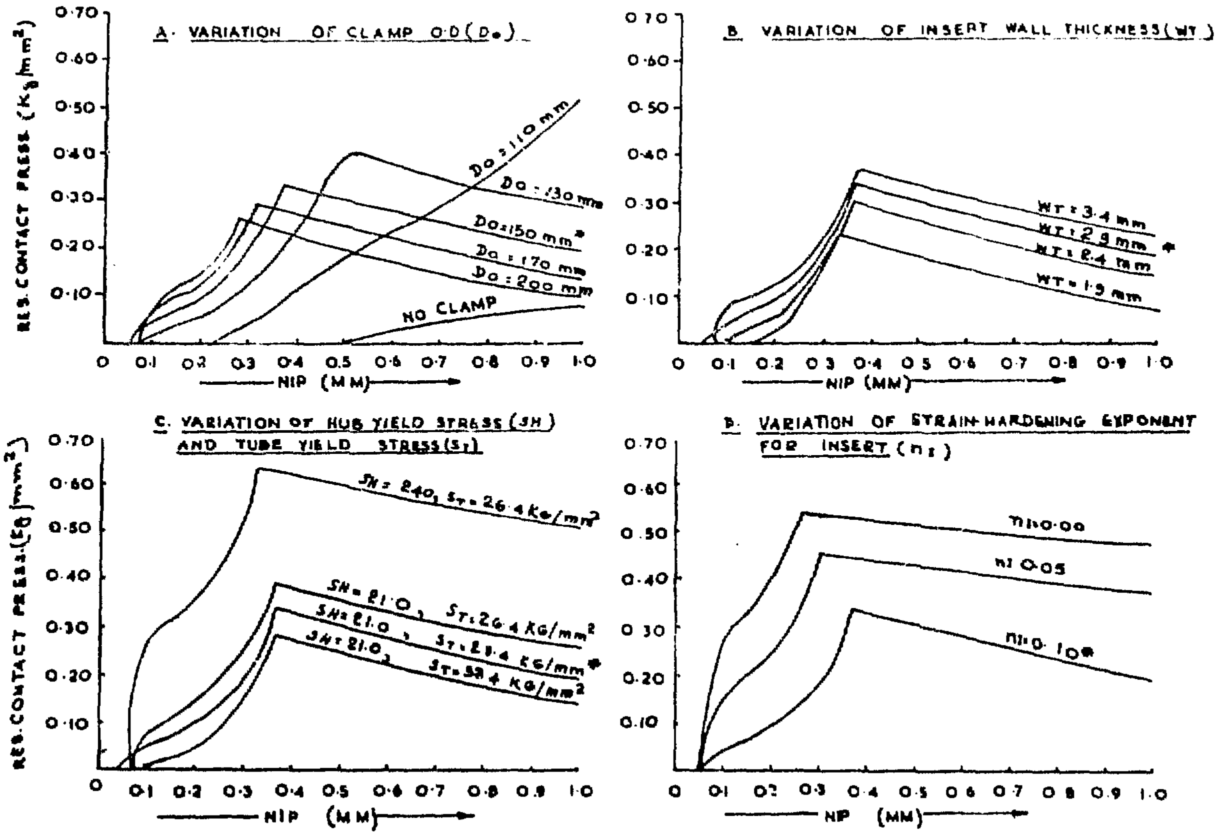
1. E.D. Grimison and C.H. Lee, "Experimental Investigation of Tube Expanding"; trans.ASME 65, 497-505 (1943).
2. A. Nadai, "Theory of the Expanding of Boiler and Condenser Tube Joints Through Rolling"; trans. ASME 65, 865-880 (1943)
3. J.N. Goodier and G.J. Schoessow, "The Holding Power and and Hydraulic Tightness of Expanded Tube Joints : Analysis of the Stress and Deformation": trans.ASME 65, 489-496 (1943)
4. F.F. Fisher and G.J. Brown, "Tube Expanding and Related Subjects"; trans. ASME __, 563-575 (1954).

FIG: 1 JOINT CONFIGURATION AT THE BEGINNING OF EXPANSION



DIMENSIONS & MATERIAL PROPERTIES FOR REFERENCE JOINT

COMPONENT	INTERNAL DIA MM	EXTERNAL DIA MM	YIELD STRESS KG/MM^2	POISSON'S RATIO	ELASTICITY MODULUS KG/MM^2	STRAIN HARDENING EXPONENT
INSERT	74·50	80·30	17·50	0·30	21000	0·10
TUBE	80·30	82·30	29·40	0·40	10000	0·05
HUB	83·35	96·00	21·00	0·30	21000	0·10
CLAMP	96·00	150·30	LARGE	0·30	21000	



* REFERENCE CASE

FIG.2. EFFECT OF DIFFERENT VARIABLES ON RESIDUAL CONTACT PRESSURE BETWEEN TUBE AND HUB