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DEVELOPMENT OF NUCLEAR QUALITY HIGH PRESSURE VALVE BELLOWS IN CANADA

by

P. JANZEN and C.J. ASTILL

Presented at the Canadian Nuclear Association 1978 Annual
International Conference, Ottawa, Canada, 1978 June 11-14

Chalk River Nuclear Laboratories
Chalk River, Ontario

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Développement au Canada de soufflets à soupape sous haute pression de qualité nucléaire*

par

P. Janzen et C.J. Astill

Résumé

Concurremment avec la décision d'employer des soupapes nucléaires scellées par soufflets à tiges lorsque cela est possible dans les centrales CANDU (Canada Deutérium Uranium) de taille commerciale, l'EACL a entrepris de développer une technologie de soufflets à soupape à haute pression. Ce programme comprend le développement d'un savoir-faire pour fabriquer des soufflets à soupape à haute pression améliorés de concert avec un fabricant canadien.

Ce rapport décrit l'évolution du procédé de fabrication de soufflets bi-étagés comprenant: (1) la fabrication de sections discrètes de tubes de précision à fine paroi et téléscopiques -- depuis la préparation de bandes brutes par meulage latéral et formation de bords jusqu'au soudage longitudinal; (2) formation de soufflets à partir d'assemblages de tubes en utilisant une nouvelle combinaison d'emboutissage mécanique vers l'intérieur suivi d'un emboutissage hydraulique vers l'extérieur.

Des soufflets en Inconel 600 et en Inconel 625 ont été fabriqués et évalués. Les résultats des essais indiquent une performance allant de comparable à améliorée par rapport à d'autres soufflets de haute qualité.

*Rapport présenté au Congrès annuel 1978 de l'Association nucléaire canadienne, tenu à Ottawa, Canada, du 11 au 14 juin 1978.

L'Energie Atomique du Canada, Limitée
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ABSTRACT

Concurrent with the decision to use bellows stem sealed nuclear valves where feasible in commercial-scale CANDU (Canada Deuterium Uranium) plants, Atomic Energy of Canada Limited undertook to develop an indigenous high pressure valve bellows technology. This program included developing the capability to fabricate improved high pressure valve bellows in conjunction with a Canadian manufacturer.

This paper describes the evolution of a two-stage bellows fabrication process involving: (1) manufacture of discrete lengths of precision thin wall telescoping tubes -- from preparation of strip blanks through edge grinding and edge forming to longitudinal welding; (2) forming of bellows from tube assemblies using a novel combination of mechanical inward forming followed by hydraulic outward forming.

Bellows of Inconel 600 and Inconel 625 have been manufactured and evaluated. Test results indicate comparable to improved performance over alternative high quality bellows.

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DEVELOPMENT OF NUCLEAR QUALITY HIGH PRESSURE VALVE BELLOWS IN CANADA

1. OBJECTIVE

Atomic Energy of Canada Limited, in light of its experience, decided to undertake to establish a Canadian source of nuclear bellows. In 1973 January United Flexible of Canada Limited (UFC) was contracted to develop the technology and the manufacturing capability to produce

1. Low and medium pressure bellows for general sealing applications such as Fuel Channel Annulus, Ion Chamber and Shield Tank seals, and

2. High pressure bellows for use as valve stem seals.

The first objective was achieved and commercial production commenced in mid-1974. Subsequently UFC embarked on the second objective.

This paper describes the bellows fabrication process that evolved, including: (1) the manufacture of discrete lengths of precision thin wall telescoping tubes; (2) the forming of multi-ply tube assemblies into bellows using a novel combination of mechanical inward rolling followed by hydraulic outward forming.

The specific goal was to fabricate a formed Inconel 600 high pressure bellows to fit the 19 mm "900 lb ANSI rated" globe valve installed in the Pickering Nuclear Generating Station-A.

2. PERSPECTIVE

Why did AECL want to develop the technology and establish a Canadian manufacturer to produce bellows? Several more obvious reasons follow.

First, with no domestic source of nuclear quality bellows, Canada was obliged to rely on foreign suppliers. When several bellows sealed valves (BSV's) in Pickering NGS-A failed prematurely, the supply of replacements threatened to become a problem.

Second, bellows manufacturers were skeptical about the likelihood of developing bellows for the upgraded service conditions of newer reactor designs.

Third, bellows forming technology is in a state of development and with potential for improvement. This was indicated by studies initiated at Chalk River Nuclear Laboratories (CRNL) which showed a surprising variability in bellows configuration, method of fabrication and most dramatically in price.

Fourth, this was an opportunity to increase further the Canadian content of CANDU* nuclear generating stations. Several valve manufacturers

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* CANDU - CANada Deuterium Uranium

were well established in Canada. If bellows manufactured in Canada were available to them, complete BSV's could be manufactured within Canada.

Many prospective companies were contacted to assess their desire and ability to perform the necessary development work. UFC was judged best able to meet AECL's objectives.

At the time UFC designed and fabricated a range of low pressure expansion joints and related products in its Richmond Hill, Ontario plant. Its management was keenly interested in entering the nuclear field, enough to have initiated development on the first objective. It possessed considerable expertise in bellows fabrication in its production and design groups, and the personnel to be involved were enthusiastic.

3. BELLOWS AS VALVE STEM SEALS

Bellows are thin walled circumferentially corrugated cylinders made from seamless or welded tube. Figure 1 presents the nomenclature as used in this paper. With typical wall thicknesses in the range of 0.15 mm to 0.30 mm, a single ply bellows will be limited to low pressure applications. High pressures are accommodated by an increase in the number of plies. Currently bellows are finding application at pressures exceeding 14 MPa. A cross-sectional view of a three-ply bellows is shown in Figure 2. Figure 3 depicts the bellows as a valve stem seal.

Initially BSV's, all globe valves, were adopted for pipes up to 50 mm diameter. Subsequently, the range was extended to 150 mm diameter pipe. Bellows design data for the 19 mm globe valve included:

Inner diameter	:	∿ 20 mm
Outer diameter	:	∿ 30 mm
Ply thickness	:	0.20 mm
Operating pressure	:	11.0 MPa
Operating temperature	:	300^{o}C
Cyclic life	:	5000 cycles minimum

4. TUBE FABRICATION

4.1 Conventional Tube Fabrication Techniques

Why did AECL opt for development of a thin wall tube manufacturing process? According to UFC, the integrity of the seam weld of tubing currently available left much to be desired. The schematic of the German Mill, Figure 4, is typical of present production techniques. This machine is used to produce continuous lengths of commercial quality tubing. This same machine is also used to produce tubing from which nuclear quality bellows are made. Examination of the process reveals its limitation.

Strip material, sheared to the appropriate width is drawn from a roll through plastic boats and finally through former rolls to progressively form it into a cylindrical shape. It then enters the conical opening to a sizing heat sink bush where the edges are welded together as they pass beneath the torch. Two typical cross sections of this tube are shown in Figure 5 and 6 which indicate undesirable features resulting from considerable variation in presentation of the butted edges at the time of welding. (Figure 7 shows a typical cross section of AECL welded tube.) Yet another disturbing feature applicable to seamless and seam welded tubing is that the manufacturers' minimum mill run is large, usually in the order of ∿150 m. An order for a comparatively small number of multi-ply bellows involves the purchase of several mill runs of different sizes of tubes and ultimately storage of surplus material. This factor alone provides incentive for a bellows manufacturer to size or stretch a tube to the next largest size required for plying by the method shown in Figure 8. This involves drawing the tube over an expander bush which stretches the walls beyond the elastic limit to produce an inside diameter equivalent to the original outside diameter plus annular clearance. There is of course no guarantee that thinning of the wall is uniform. Most manufacturers expand a tube to make just one extra ply as sizing beyond this could further jeopardize the integrity of the tube.

4.2 Fabrication of Discrete Lengths of Multisized Tubes

Fabrication of precisely sized seam welded tubes depends upon carefully controlled operations. The manufacturing process must possess the following essential design features.

a) Butted edges at the seam weld must be square and free from burrs and shearing deformation.

b) The blank must be accurately sized to produce the desired tube diameter.

c) The butted edges of the tube blank must be perfectly presented to the welding torch and the blank material must be firmly gripped between heat sinks accurately located on each side of the butted edges.

d) A shielding gas should be used both outside and inside of the tube during the welding pass.

e) The process should be sufficiently versatile to produce accurately sized tubes of varying diameters which can be plied without severe sizing operations.

The process operations finally adopted are shown in Figure 9. A blank 0.75 m long is sheared to the finished width plus a small grinding allowance. A scissors type centering fixture locates the blank while a service location slot is punched in each end. A special purpose grinding machine with a wheel spindle located on each side of the table is used to grind a stack of ten blanks to width. The stack of blanks is centrally located by the service slots fitting on keys protruding from each end of the surface of the table. A heavy beam clamps the blanks firmly onto the table during the edge grinding operation. The edges are finish ground to the desired width equidistant on each side of the service slots.

Individual blanks are again located by the service slots on a special rolling mill and the edges are preformed to the approximate radius of the finished tube.

A cross section of the tube as it is located on the final forming and welding machine is shown in Figure 10. An axially collapsing tool steel mandrel with a copper heat sink liner wrapped around it is located on a cradle and tangentially positioned with retractable locating keys which also locate the sandwiched tube blank and liner. Rotation of the two former rolls is controlled to produce slight skidding between their outside surface and the tube blank as they are advanced to the fully clamped position shown. A pneumatic load is then applied to the heat sink fingers which clamp the tube blank tightly against the heat sink liner. A shielding gas flow is passed through the gas gallery as the torch is traversed along the butted joint. The weld produced by this process is of uniform and high quality (Figure 7). Tubes can be repeatedly produced and, by changing the thickness of the heat sink liner, tubes can be produced which telescope to form multi-ply tube assemblies with extremely small annular clearances.

The capability of producing only the amount of tubing which is required for a given number of bellows has obvious economic appeal. Some automation of the development machines would not only produce a better product but also a competitive product.

Most tubing currently used is made from comparatively ductile material, stainless steel, Inconel 600, etc. We have recently produced tubing from Inconel 625 which has a much higher tensile strength and other characteristics favourable for bellows application.

5. BELLOWS FORMING

5.1 Forming Methods

Bellows forming processes which are relevant to our application employ two basic techniques: mechanical rolling and hydrostatic forming. Each possesses advantages and disadvantages. Mechanical rolling, which forms one convolution at a time, involves low set up charges and lends itself to low volume production. But it generally causes localized, at times excessive, ply thinning, is limited to the number of plies and can result in unsymmetrical convolution shapes. Hydraulic forming is the most popular, high volume production method in which all convolutions may be formed simultaneously. However, the convolution roots are not work hardened, some thinning of the crowns occurs and the convolution depth is limited by the outward formability of the material.

Combinations of the two techniques have been developed which attempt to optimize bellows characteristics. One such method is the "Press-and-roll" technique. In its first stage, circumferential corrugations are created sequentially and at regular intervals by forcing material in the tube assembly outwardly into a designed die. The corrugated assembly is then passed to a mechanical forming device in which the material between the corrugations is formed inwardly. An axial compression to reduce convolution pitch completes the forming process. Manual operations in the process allow operator skills to affect the quality of bellows obtained.

Bellows fatigue tests conducted at CRNL*showed that practically all bellows failures occur at the convolution root. Therefore the state of the material and convolution shape at the root are crucial aspects.

A survey and examination of current techniques led to the adoption of the novel "roll-and-press" method of forming bellows. To ensure better control of root shape, the root is inwardly rolled first. Subsequently, the material between corrugations is hydrostatically formed outwardly into dies. Better process control seemed possible. Less development machinery would be required. Finally, two in-house inward rolling operations using bronze and stainless steel actually indicated a minute ply thickening at the root, a promising recommendation for the method.

5.2 Inward Rolling

An existing mechanical bellows forming machine was adapted for development of the inward rolling technique. A freely rolling external die of a developed configuration impinges on the material forcing it inwardly as shown in Figure 11. The tube is indexed and the operation repeated. Three and four-ply tube assemblies were rolled but the latter strained the capability of the machine.

The following aspects of the operation required consideration.

(1) Depth of preform: this is related to tool width (the thinner, the deeper), the number of plies (the fewer, the deeper), the material (the more ductile, the deeper), the speed of rotation, and the rate of tool penetration (wrinkling if too sudden, excessive work hardening if too slow).

(2) Tool configuration: according to analysis the greater the root torus radius, the lower the stresses due to pressure and axial movement per convolution; a round die tends to cause a peak in the root during the collapse operation and so a "flat" was incorporated.

(3) Inner support: this was found necessary to prevent wrinkling and ensure a proper form of the inner ply.

(4) Corrugation pitch: this affects the degree of ply thinning at the convolution crown and the convolution depth (directly proportional).

* CRNL - Chalk River Nuclear Laboratories

5.3 Outward Hydroforming

The corrugated tube is then installed in the hydroforming machine (Figure 12). In the current mode, individual external dies are fitted to the preforms and constrained. A special die is positioned at the ends to control the degree of material draw-in of the end convolutions. The die shape is identical to the inward forming tool but the faces deviate 5° from the transverse plane. Glycerine is introduced into the constrained tube assembly and brought to a pressure sufficient to expand the cylindrical sections into the dies. At a predetermined pressure level the dies are pushed together, reducing the crown width. The internal fluid is then drained and the dies are removed. The tube assembly now possesses near U-shaped convolutions. Finally the bellows is axially compressed until adjacent convolutions contact and then is allowed to spring back to yield S-shaped convolutions, the ideal shape for applications combining pressure and axial movement.

A near optimum convolution shape was defined on the basis of stress analysis. Because of the non-uniform material properties, however, experimental evidence in the form of fatigue test results was required to obtain the convolution shape for optimum bellows performance.

The following aspects were emphasized in the development work, analytical and experimental.

1. Degree of outward forming: influenced by the space limitations, pressure level and stroke of the application, material ductility and preform pitch.

2. Convolution root and crown shape: determined by the die shape and the final collapse operation.

3. Forming pressure level: dependent upon the number of plies, the material yield stress and its strain hardening characteristics.

5.4 Comparison of Inconel 600 and Inconel 625 Forming Characteristics

Inconel 625 has mechanical properties which make it superior to Inconel 600 as bellows material: a higher yield and tensile strength and better fatigue resistance. Although a slight adjustment in the tube welding process was required, it yielded a weld better than that for Inconel 600. Inconel 625 also work hardens more rapidly and to a higher level than Inconel 600. Inward rolling therefore required higher loads for comparable convolution depth, and outward forming required slightly higher pressure. The spring-back after collapsing was noticeably greater for Inconel 625 due to its higher yield strength.

5.5 Attachment Welding

The cuffs of the formed bellows are trimmed and fitted and welded to appropriately designed end pieces. It is advisable that this operation be performed by the bellows manufacturer because of the skill required to weld the multi-ply thin wall component, frequently to a dissimilar metal. A well executed field weld involving the more robust end pieces and the relevant component of equipment is unlikely to damage or induce unfavourable characteristics to the vulnerable bellows element.

6. STATUS OF VALVE BELLOWS DEVELOPMENT

6.1 Development of Technology

Although periodic readjustment of the development machines is required, tube welding and bellows forming are routine operations. Several samples of Inconel 600 as well as Inconel 625 bellows have been fabricated for evaluation and fatigue testing. Results of these tests are motivating further development of the process to improve the cyclic life of bellows.

6.2 Fatigue Test Results of Prototype Bellows

Table 1 shows the progress of development. Although the incremental improvements were not individually statistically significant, their collective effect yielded a statistically significant improvement. Compare, for example, Sample F and Samples A and C. The modifications which probably yielded the improved cyclic life were changes in convolution shape, and included a deepened convolution, an increased root torus radius and a reduction in the crown torus radius.

Probably the most noteworthy data are those concerning the performance of the prototype Inconel 625 bellows. This superior performance is probably due to the good fatigue characteristics of Inconel 625. For service in nuclear steam supply systems Inconel 625 has either comparable or superior properties to Inconel 600, and these results indicate that its adoption as bellows material would significantly improve the reliability of bellows valve stem seals.

Performance of Inconel 600 bellows is comparable to that of good quality bellows available from alternative sources. Results to date indicate further improvements to be achievable for both materials. Only further development will determine the limits of bellows performance.

6.3 Commercial Bellows Production

The tooling and machines used to produce the prototype bellows were designed for development purposes featuring numerous adjustable settings and manual control. To be economically justifiable, production of nuclear bellows would require automation of most operations in the process. This would not only speed the operation but also reduce the effect of the human element. An elementary economic study performed by UFC and based on development machinery indicated the process to be comparable in cost to the press-and-roll technique.

The step from prototype production on development machines to commercial production on automated machines would likely require a modest amount of development. Other sizes of bellows than that developed would be required to meet the demand for applications. Changes in ply thickness and convolution shape may be warranted to optimize performance in special applications. New materials may be considered.

7. SUMMARY

The technology to fabricate small high pressure nuclear quality bellows has been developed in Canada. It involves novel tube welding techniques and a novel roll-and-press bellows forming process. Results of tests of prototype bellows indicate comparable to improved performance over available alternative high quality bellows. Inconel 625 bellows especially hold a promise of a significant improvement in reliability of bellows valve stem seals. Some business decisions are now required to commercialize production and establish markets.

TABLE 1 : FATIGUE TEST RESULTS OF PROTOTYPE BELLOWS FROM UFC INDICATING THE EFFECT OF DEVELOPMENT AND MATERIAL

SAMPLE	A	C	E	F	H
No. of Plies	3	3	3	3	3
Total Pressure MPa	10.34	10.34	10.34	10.34	10.34
Cyclic Life	4390 4458 7273 7853	4253 4397 4694 5302 6980	3986 6080 8070 10998	5895 7745 8132 9102 11201	39727 107048 66552 51121
Average Cyclic Life	5780	5040	7050	8230	61676
Error Variance (Nat. log)	.311	.201	.425	.235	.424
Axial Stroke (15%) mm	9.6	9.1	12.2	10.2	12.2
Material Inconel	600	600	600	600	625

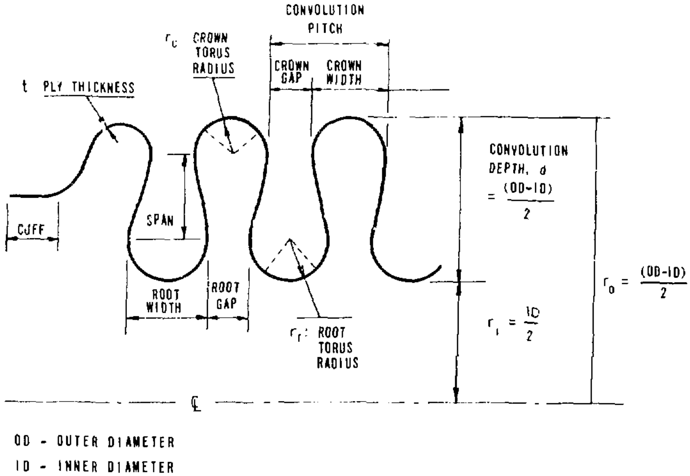

FIGURE 1 : BELLOWS NOMENCLATURE

FIGURE 2 : CROSS SECTION OF TYPICAL 3-PLY BELLOWS

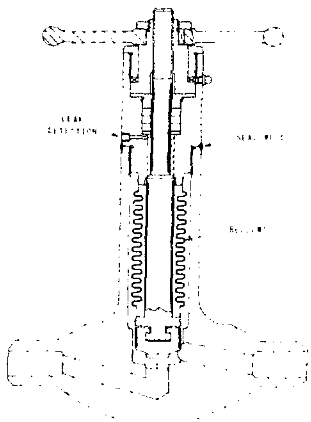

FIGURE 3 : TYPICAL BELLOWS SEALED VALVE

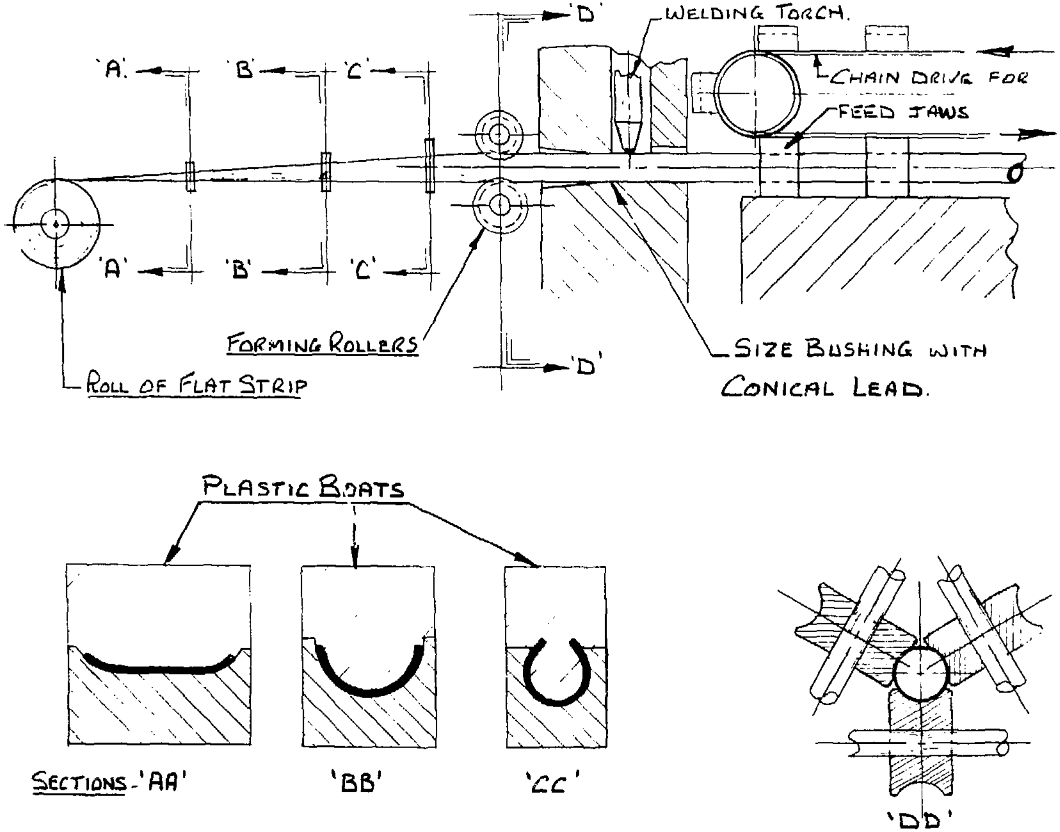

FIGURE 4 : SCHEMATIC OF THE GERMAN MILL TUBE WELDING MACHINE

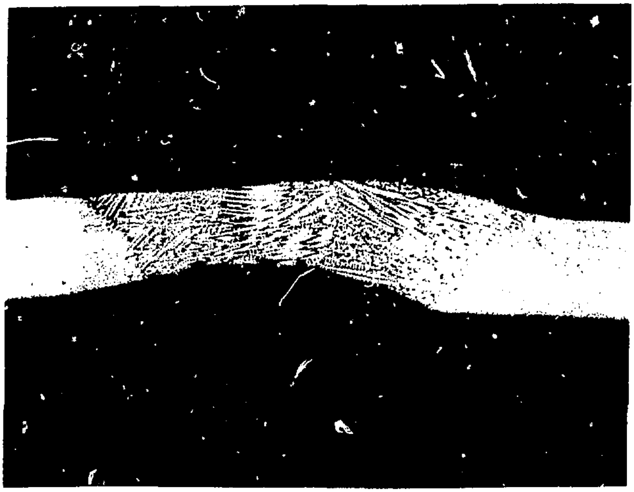

FIGURE 5 : MISALIGNED EDGES OF WELDED GERMAN MILL TUBE

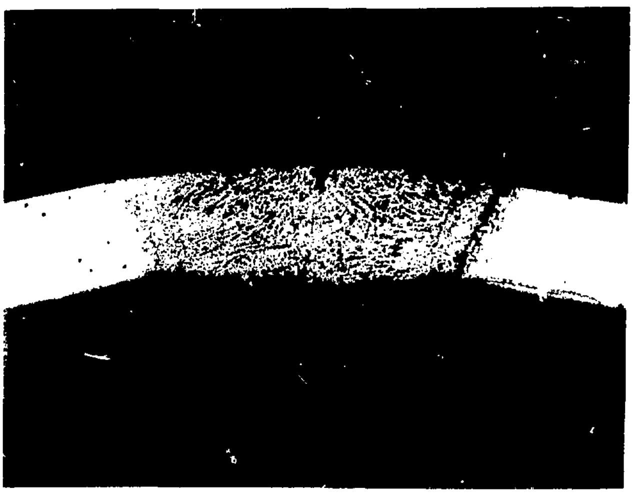

FIGURE 6 : PEAKED EDGE PRESENTATION IN WELDED GERMAN MILL TUBE

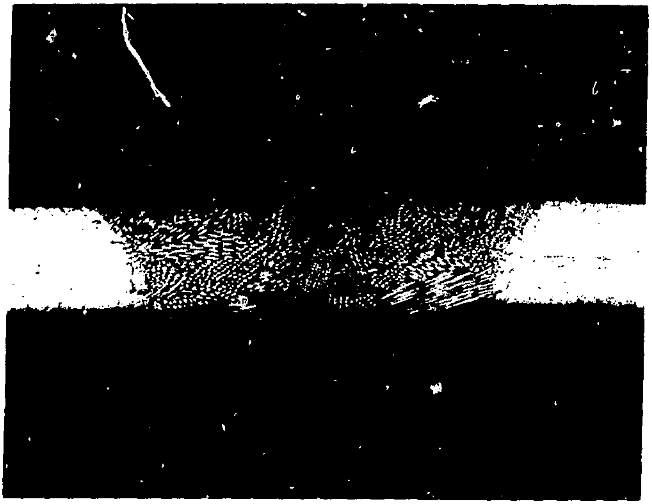

FIGURE 7 : TYPICAL TUBE WELD DEVELOPED AT UFC

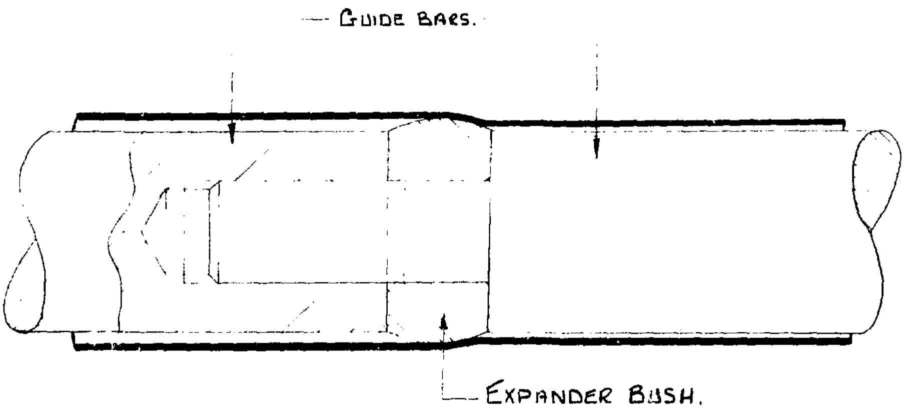

FIGURE 8 : TUBE SIZING OPERATION

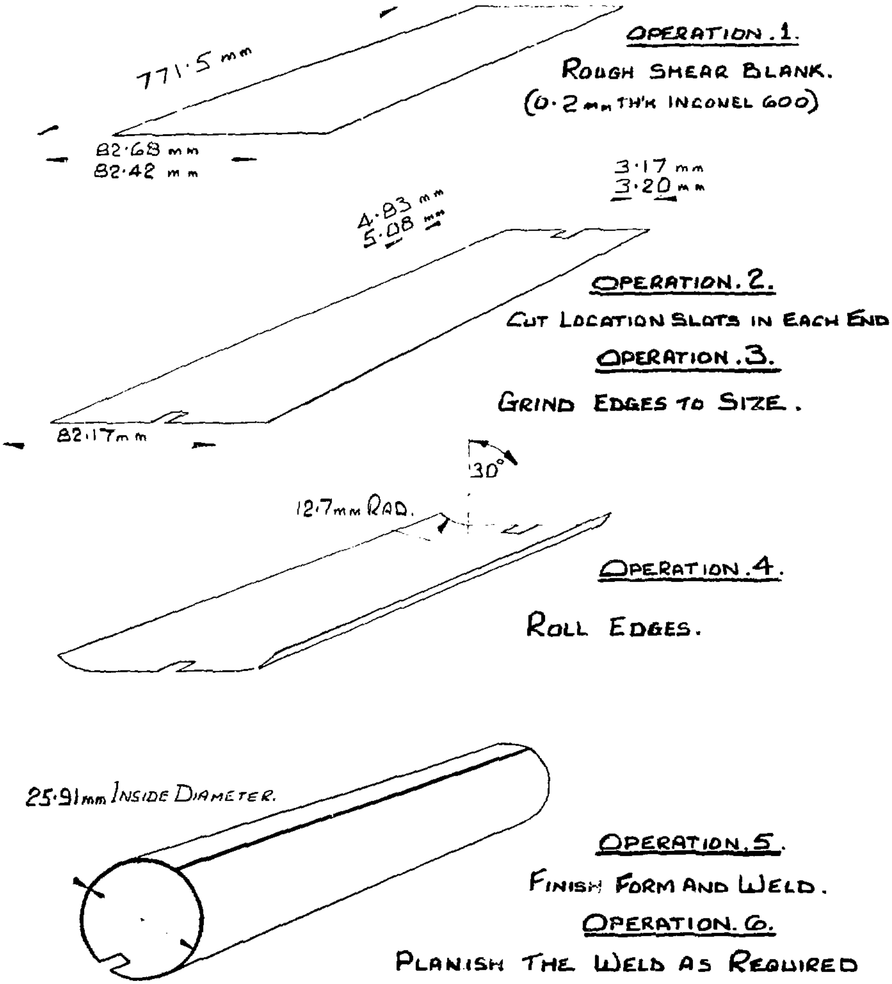

FIGURE 9 : TUBE FABRICATION PROCESS

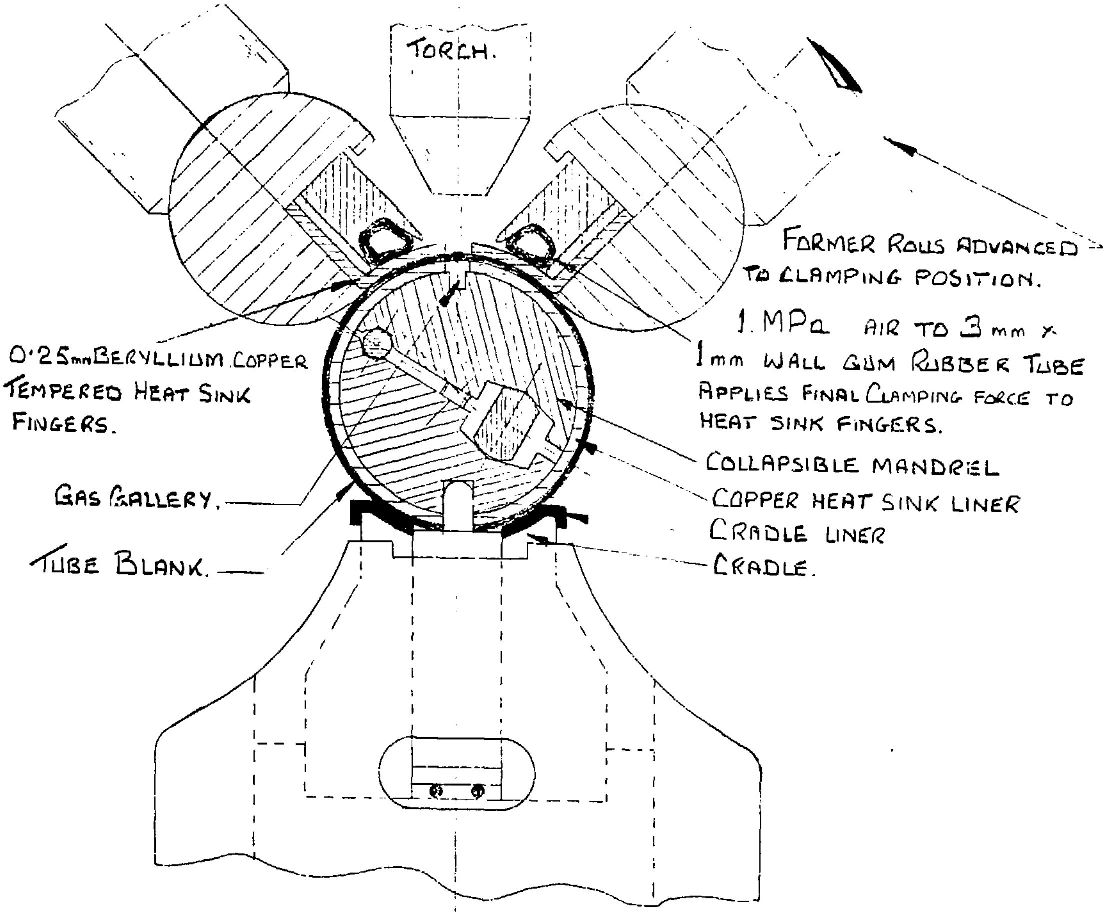

FIGURE 10 : CROSS SECTION OF FINAL ROLLING AND WELDING MACHINE

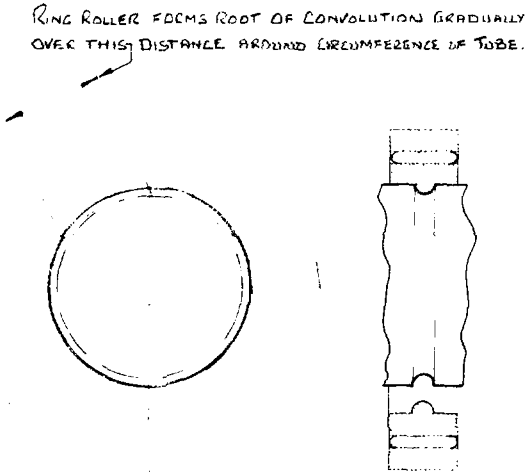

FIGURE 11 : INWARD ROLLING OPERATION

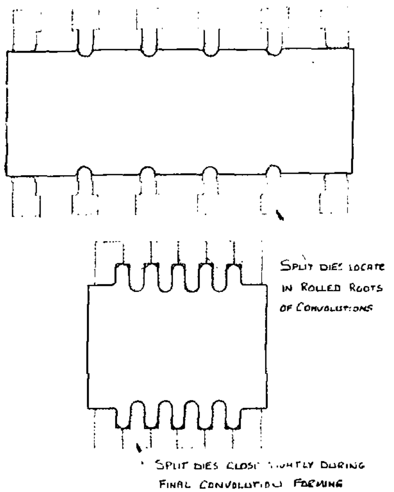

FIGURE 12 : OUTWARD HYDROFORMING OPERATION

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