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**A METHOD FOR EVALUATING
THE MECHANICAL PERFORMANCE
OF THIN-WALLED TITANIUM TUBES**

P.M. MacKenzie, C.A. Walker, J. McKelvie

**Department of Mechanical Engineering,
University of Strathclyde,
Glasgow G1 1XJ,
Scotland, UK .**

peter.mackenzie@strath.ac.uk

Tel: 0141 548 2045

Fax: 0141 552 5105

19 **ABSTRACT**

20 A method which was developed to compare the stress-strain properties of three types of
21 thin-walled, commercially pure titanium tubes is presented. The tubes were of types
22 intended for use in large heat-exchanger applications and were to be subjected to
23 significant plastic deformation during subsequent assembly processes. It had been
24 anticipated that small differences in chemical composition and tube-drawing treatment
25 would produce quite different characteristics. It is known that the properties of titanium
26 can exhibit considerable degrees of anisotropy, especially for wrought products;
27 although axial properties of the materials could be evaluated using standard test
28 equipment and procedures, a novel testing system had to be designed to allow the
29 circumferential properties to be assessed. Significant differences between tube types
30 were observed and anisotropic material behaviour was apparent.

31

32 **Keywords:-** anisotropic; commercially pure titanium; ductility; mechanical testing;
33 hydraulic; tubes.

34 **INTRODUCTION**

35 Titanium and its alloys have desirable blends of properties such as low density, high
36 strength and high stiffness, each of which makes them attractive for many structural
37 applications. Coupled to these benefits are exceptional levels of resistance to corrosion
38 and oxidation and, compared with aluminium alloys, distinctly better creep-resistance.
39 For these reasons, the use of titanium and its alloys can be justified economically in an
40 increasing range of high-integrity areas, from aerospace to petrochemicals (and not
41 forgetting to mention the growing market in sports goods).

42

43 Approximately 25% of the market for metallic titanium is made up of the commercially
44 pure (CP) form. CP titanium is, in effect, an alloy of titanium, oxygen and traces of
45 several other elements. Although, in all of the various varieties which come under the
46 CP designation, metallic titanium makes up in excess of 99% of the content, the small
47 fractions of other elements which may be included can influence the mechanical
48 properties to a very significant degree. Most notably, small, controlled amounts of
49 oxygen are dissolved in solid solution to produce increases in strength but, ultimately,
50 with a significant reduction in ductility. CP titanium generally displays good ductility
51 and can be forged, rolled, drawn or extruded quite straightforwardly but its hexagonal
52 close packed (α -phase) structure does limit formability. In addition, the textures
53 developed in wrought products for α - titanium and its alloys can have a marked effect
54 on the mechanical properties of the finished material and distinctly anisotropic material
55 behaviour can be a common feature [1 - 6].

56

57 The work presented here was focussed on evaluating mechanical properties of thin-
58 walled CP titanium tubes intended for use in heat exchangers. The key justification of
59 the work was that, during the fabrication process, expansion of tubes into tube-sheets
60 produces high levels of plastic deformation of the tube material circumferentially [7,8]
61 and, to this end in particular, a novel method for assessing the response of the material
62 in the circumferential direction was required.

63

64 **SPECIMEN MATERIALS**

65 Specimens of three different types of drawn tube were used in the investigation. Details
66 of oxygen content together with tube dimensions are summarised in Table 1.

67

68 Figure 1 contains representative micrographs of the grain structure of each of the three
69 specimen groups, designated Types 'A', 'B' and 'C'. Type 'A', the only vacuum
70 annealed sample, shows very much larger grain diameter (by a factor of 4 to 5
71 approximately [9]) than do either of the other types. The three dimensional nature of the
72 texture could not be assessed by optical microscopy alone and was beyond the scope of
73 the present work.

74

75 **AXIAL AND CIRCUMFERENTIAL LOADING CONFIGURATIONS**

76 Axial testing of the tubes was performed in a relatively straightforward manner, as
77 prescribed in [10], the British Standard. This requires quite simply that the tube ends,
78 through which loads were to be applied, be reinforced in a prescribed manner; it also
79 places requirements on the rate of loading and the method of recording results (these are

80 discussed below). Specimen tube lengths of 400 mm satisfied the requirement of the
81 standard test. Loads were applied using an Instron 1342 servo-hydraulic test machine.

82

83 By contrast, an entirely novel setup had to be designed in order to enable
84 circumferential loading of the material, with axial stresses, up to yield point at least,
85 eliminated as far as possible; there is no published prior art with regard to this.. Whilst
86 there is a wealth of literature relating to the contiguous technology of hydroforming, for
87 example, [11 - 14], this almost invariably deals with the application of intentional
88 biaxial loading conditions. Indeed, [13] describes a method of testing tubular specimens
89 with deliberately induced biaxial loads, so as to simulate the conditions found in the
90 hydroforming process. The hydraulic test rig constructed for the present purpose is
91 shown schematically in Figure 2. It was designed to perform two main functions: to
92 ensure loading of the specimens in the desired manner, i.e., no, or minimal, axial
93 loading up to yield; and to enable controlled application of the loading or expansion,
94 this being achieved by having the Instron test machine previously mentioned adapted to
95 provide the driving force for the rig. As shown in Figure 3, the test rig was mounted
96 between the platens of the test machine, thereby enabling full feedback control of the
97 pressure applied to the specimens.

98

99 **SPECIMEN SEALING ARRANGEMENTS**

100 The test rig also incorporated the specimen holder consisting of a removable steel core,
101 with seals, mounted between a crosshead and the pump body. Specimens of dimensions
102 given in Figure 4 were mounted on the core, and through this, the pressurised hydraulic
103 oil was delivered.

104

105 Initially, it had been intended that the specimen sealing arrangement would consist of a
106 bespoke nitrile rubber bladder but this proved to be unsatisfactory. From axial test
107 results, it had appeared that pressures of approximately 100 MPa might be required in
108 order to take the tubes to failure. This system was capable of containing only 10% of the
109 target value. Bonding the seal to the central core using cyanoacrylate adhesive produced
110 a substantial improvement in performance but, at seal failure pressures of about 60
111 MPa, this still fell short of the programme requirement.

112

113 In order to minimise axial loads up to yield, it was essential that the tubes be free-
114 floating, i.e., the ends could not be plugged during the tests. To this end, an alternative
115 technology to the bladder seal proved to be entirely satisfactory. This consisted of a
116 setup using conventional nitrile rubber 'O'-ring seals on a special core, in tandem with
117 spiral PTFE backing washers to prevent seal extrusion (Figure 5). Steel rings of
118 thickness 2mm and diameter 0.2mm greater than those of the specimens were used to
119 support the specimen at the point of contact with the 'O'-rings. This setup allowed
120 pressures up to 140 MPa to be contained.

121

122 A key feature of the design is that the pressure end-loads imparted through the specimen
123 cores were supported by, on the one hand, the pump body, and on the other, by the
124 retaining cross-head mounted on reaction columns. By using two-piece cores, a
125 potential problem in the oil-way at the core to body seal was eliminated since it was
126 possible, by selecting appropriate dimensions, to ensure that the outward hydraulic force

127 tending to open the seal was always more than balanced by the pressure force on the
128 core from within the specimen.

129

130 Prior to each test, the hydraulic system, including the fresh specimen, was recharged
131 with working fluid (Esso Nuto-H46) by first evacuating it to ensure no air pockets
132 remained.

133

134 **TEST PROCEDURE**

135 Instrumentation comprised: Instron 100kN load cell (for the axial loading
136 configuration); Shape 140 MPa pressure transmitter (for the circumferential loading
137 configuration); a purpose-built clip-gauge diametrical strain transducer, Figure 6,
138 essentially, two spring steel blades to which were attached four 6.35mm 1000 Ω strain
139 gauges connected in full-bridge configuration; 6.35 mm 120 Ω strain gauges for
140 attachment directly to the specimens; signal conditioning electronics; autographic
141 recording equipment.

142

143 The specimen strain gauges were used during the hydraulic tests to monitor more
144 precisely the behaviour up to yield, the diametrical transducer being intended for
145 measurement of gross strains only. The diametrical transducer was calibrated and
146 checked for linearity using precision ground cylindrical gauge bars; in practice, it was
147 found invariably to give readings within 0.5% of micrometer measurements of the
148 specimen diameters at failure.

149

150 In evaluating the axially loaded properties of the tubes, a conventional setup was used.
151 The loads were obtained from the test machine load cell and displacements to yield
152 whilst a 50 mm gauge-length LVDT displacement transducer provided measurements of
153 extension. Elongation at failure was measured using pre-marked scales on the
154 specimens over an initial gauge-length of 50 mm.

155
156 Strain rates for both loading configurations were set to be in the range 50 to 120
157 microstrain per second up to the 0.2% proof stress level, followed by an increase in rate
158 to give failure within one additional minute.

159
160 Figure 7 shows representative traces, taken from the circumferential loading tests, of
161 internal pressure v. diametrical strain records for each of the three sample types.

162

163 **RESULTS AND DISCUSSION**

164 The results are summarised in Table 2, and in Figure 8. For the axial loading
165 configuration, the values given are for engineering stress-strain and similarly for the
166 circumferentially loaded case, except that here, instead of the tensile strength being
167 given, the circumferential stress component at failure has been presented; this was
168 calculated using the recorded internal pressure, P_f , and the final maximum internal
169 radius, r_f , at failure, to obtain the applied circumferential stress thus:

170
$$\sigma_h = \frac{P_f r_f}{t} \dots\dots\dots (1)$$

171 The tensile strength for the axial case was taken, conventionally, to be the engineering
172 stress taken from the maximum point on the load-displacement curve. The distinct yield

173 point for the Type ‘C’ record shown in Figure 7 was, to a varying degree, apparent for
 174 all Type ‘C’ specimens tested.

175

176 There are some areas to be careful of in examining these data. First of all, whilst it is
 177 reasonable to use the results for axial elongation at failure to compare the performance
 178 of the different tube types, and to use, similarly, the diametrical strain results, to make
 179 direct comparison between the axial and diametrical strain performance would be
 180 unsound. The failure by necking in the axial-loading case produces a very different
 181 plastic flow regime from that observed in the circumferentially loaded tests.

182 Furthermore, the gross changes in tube geometry observed in the circumferential
 183 loading tests progressively introduced an increasingly significant axial component of
 184 stress. In other words, the performance one is able to observe here is influenced by the
 185 specimen geometry at high strain levels; the test should be regarded as a method for
 186 assessing the material-component combination, not as a proposed standard material test
 187 *per se*. For hydraulic loading in the setup developed here, and by measuring the change
 188 in internal radius from the initial condition, r_1 , to any strained (bulged) condition of
 189 radius, r_2 , one can evaluate the magnitude of the axial hydraulic force. From this, the
 190 ratio of applied stress components is given by equation (2):

$$\begin{aligned}
 \frac{\sigma_{AXIAL}}{\sigma_{HOOP}} &= \frac{P(r_2^2 - r_1^2)}{2r_2t} \cdot \frac{t}{Pr_2} \\
 &= 0.5 \cdot \left(1 - \left(\frac{r_1}{r_2} \right)^2 \right) \\
 &= 0.5 \cdot \left(1 - \left(\frac{1}{1 + \epsilon_d} \right)^2 \right) \dots\dots\dots (2)
 \end{aligned}$$

193

194 Thus, for the maximum value of diametrical strain, ϵ_d , observed during hydraulic
195 testing (69%), an axial component of stress equal to 32% of the applied circumferential
196 stress would be induced. On the other hand, at the typical strain values (about 0.6%)
197 measured at the Proof Stress, the axial component of stress introduced due to the
198 bulging of the tubes can be shown to amount to much less than 1% of the applied
199 circumferential stress.

200

201 We can note certain other points with a considerable degree of confidence, however. It
202 is clear that, of the three batches, Type 'B', with the lowest oxygen content, exhibited
203 the lowest Proof Stress, the lowest tensile strength, and the highest ductility for both
204 loading configurations. Type 'C', having the highest oxygen content, also showed the
205 highest values for both axial tensile strength and for failure pressure in the hydraulic
206 tests, but with by far the greatest degree of scatter of the three tube types. Figure 9
207 shows two examples of circumferentially loaded Type 'C' tubes post-failure; of the
208 thirteen specimens of this type, ten failed by pinhole leak and the remaining three by
209 unstable fracture. In the cases where fracture occurred, the diametrical strain at failure
210 was at the upper end of the range for this type (73 % to 77% for the three results,
211 compared to a mean of 63%). All of the Type 'A' and Type 'B' specimens failed by
212 unstable fracture.

213

214 Given the negligible change in geometry observed at the yield point, one can reasonably
215 draw comparisons between the axial and circumferential values for Proof Stress: whilst
216 Types 'B' and 'C' showed increases of 31% and 25% respectively in the circumferential

217 direction, Type ‘A’ the large-grained vacuum annealed batch, proved to be closer to
218 isotropic in this respect showing an increase of only 14%.

219

220 In passing, it might be noted that the Hall-Petch relationship [15, 16] states that:

221
$$\sigma_y = \sigma_0 + \frac{K}{\sqrt{d}} \dots\dots\dots (3)$$

222 where the yield stress, σ_y , can be predicted as a function of: σ_0 , the “intrinsic yield” of
223 the material; d , the grain diameter; and K , a material constant. In the present case,
224 although the three sets of specimens were of near identical chemical composition (and
225 within the range prescribed for “commercially pure”), a cursory inspection of the
226 micrographs in Figure 1 confirms that Type ‘B’ has the smallest grain size and yet it
227 also has the lowest measured values of σ_y for both axial and circumferential loading
228 cases. In other words, the observed results run counter to the relationship and it
229 therefore does not hold for this situation. This can be explained in that, as previously
230 stated, the mechanical properties of CP titanium are highly sensitive to very small
231 variations in chemical composition (of the scale seen here) and, furthermore, an
232 additional determining factor, the initial level of dislocation density in the materials was
233 “as manufactured”, i.e., was not deliberately controlled for investigative purposes.

234

235 In summary, the primary objective of this work was to devise a system to enable
236 objective evaluation of, and comparison between, the properties to failure for tube
237 specimens of near-identical geometry and the results obtained from the test setup which
238 was developed have demonstrated its capability of performing this task satisfactorily.

239

240 **CONCLUSIONS**

241 A system for making comparative evaluations of, separately, the axially and
242 circumferentially loaded performance of tubular specimens of CP titanium has been
243 demonstrated. This required the development of a new experimental setup for applying
244 circumferential stresses hydraulically; using this, axial loads were essentially eliminated
245 up to specimen yield. The arrangement also enabled useful comparisons to be made of
246 ductility up to failure with circumferential loading predominant. Axial load testing
247 followed the prescribed method of a standard test procedure.

248

249 Tests were performed on three candidate tube types intended for a large-scale heat
250 exchanger application. Measured mechanical properties differed significantly between
251 the three types. All three batches displayed yield behaviour which to a significant
252 degree was dependent on orientation. Differences in performance between the tube
253 types could not be attributed directly to observed differences in average grain size. The
254 tests confirmed that tube Type 'C', having the highest oxygen content, was, generally,
255 the strongest of the three groups over both loading regimes, but at little or no cost in
256 relation to its ductility; Type 'C' was, therefore, deemed most appropriate for the
257 proposed high-integrity application.

258

259 Finally, the findings confirm that, where it is a requirement that detailed quantitative
260 comparison be made between types of CP titanium tube produced by different
261 manufacturing process, or having small differences in chemical composition, it is
262 important to conduct tests on specimens of finished tubes, there being no convenient
263 method available for reliably inferring mechanical properties otherwise.

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FIGURES AND CAPTIONS

FIGURE 1: Micrographs of Type ‘A’, ‘B’ and ‘C’ commercially pure titanium tube specimens.

FIGURE 2: Schematic of self-contained high-pressure pump and specimen holder.

FIGURE 3: Pump and specimen holder mounted in jaws of servo-hydraulic test machine.

FIGURE 4: Specimen dimensions.

FIGURE 5: Test-rig core and specimen sealing arrangement incorporating nitrile ‘O’-rings and PTFE spiral backing washers to prevent seal extrusion.

FIGURE 6: Clip gauge diametrical strain transducer (dimensions in mm). 1000 Ω strain gauges were positioned at ‘SG’. The tube diameters were measure between the 38 mm radius arcs of a pair of jaws attached to the blade ends.

FIGURE 7: Sample records of applied internal pressure v. diametrical strain from circumferential loading tests.

FIGURE 7: Summary of results of tests to failure

FIGURE 8: Examples of post-failure Type ‘C’ specimens – unstable fracture and “pinhole” failure.

Figure1
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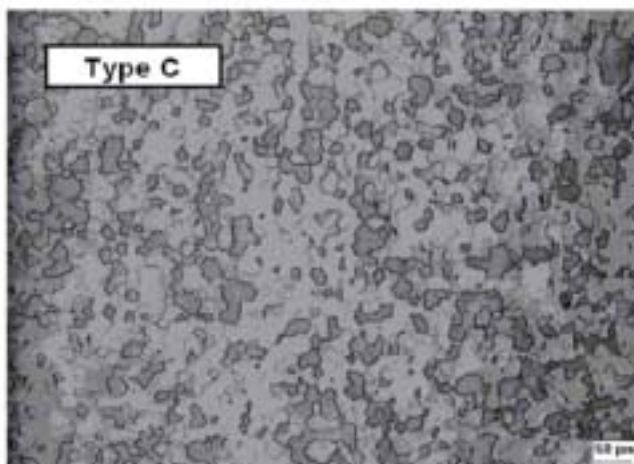
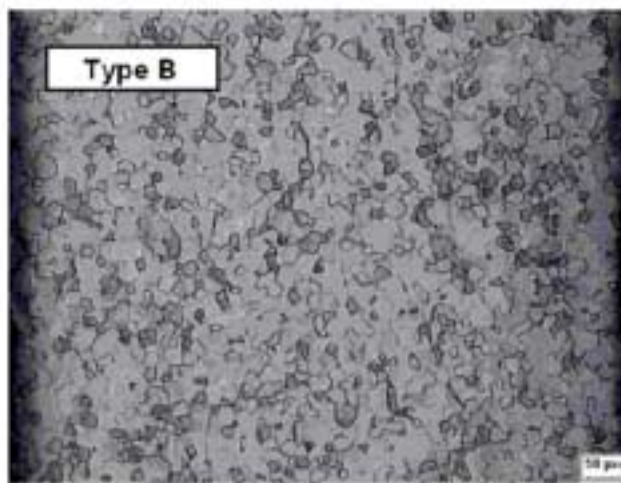
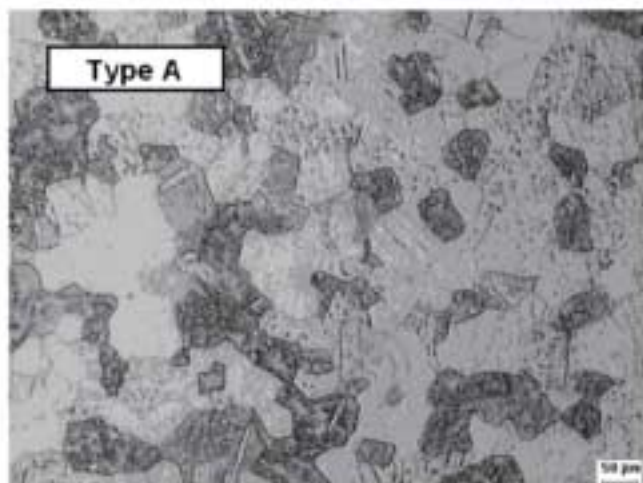


Figure 2

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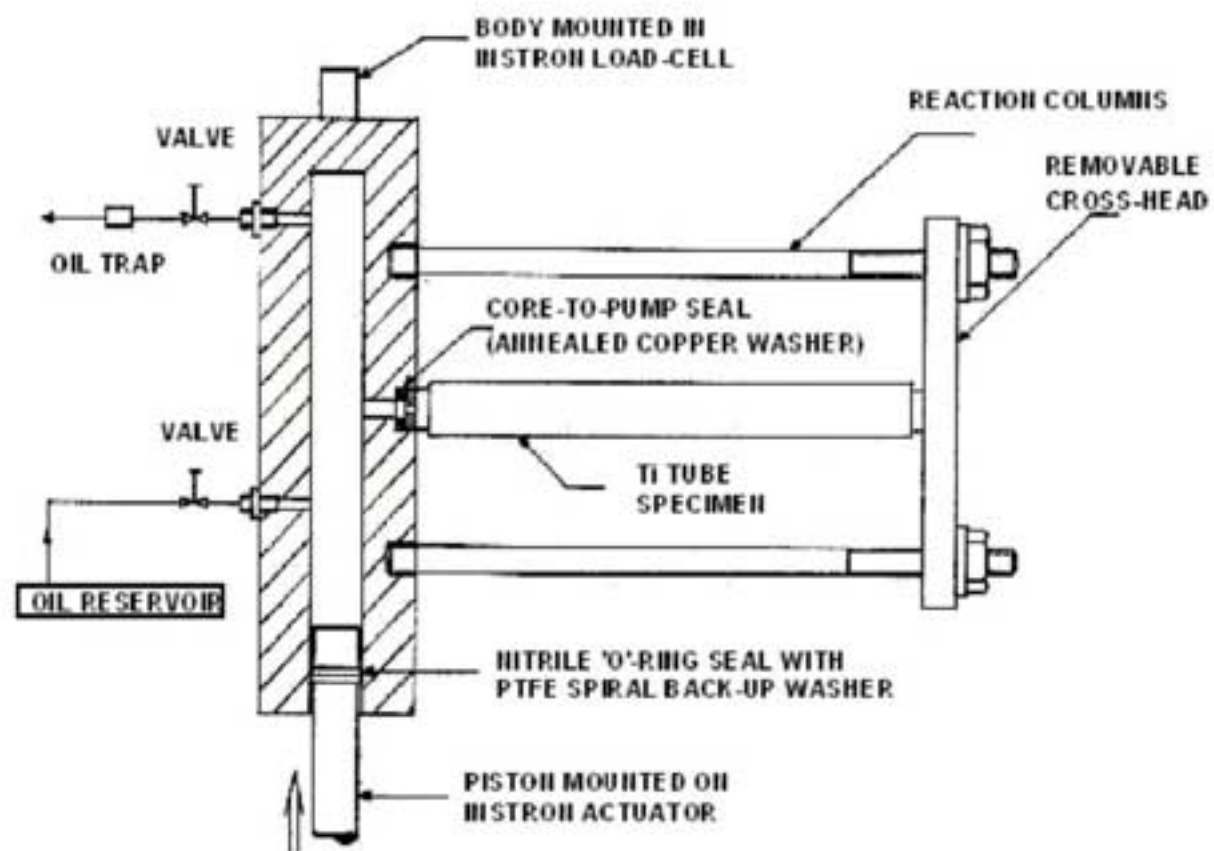


Figure3
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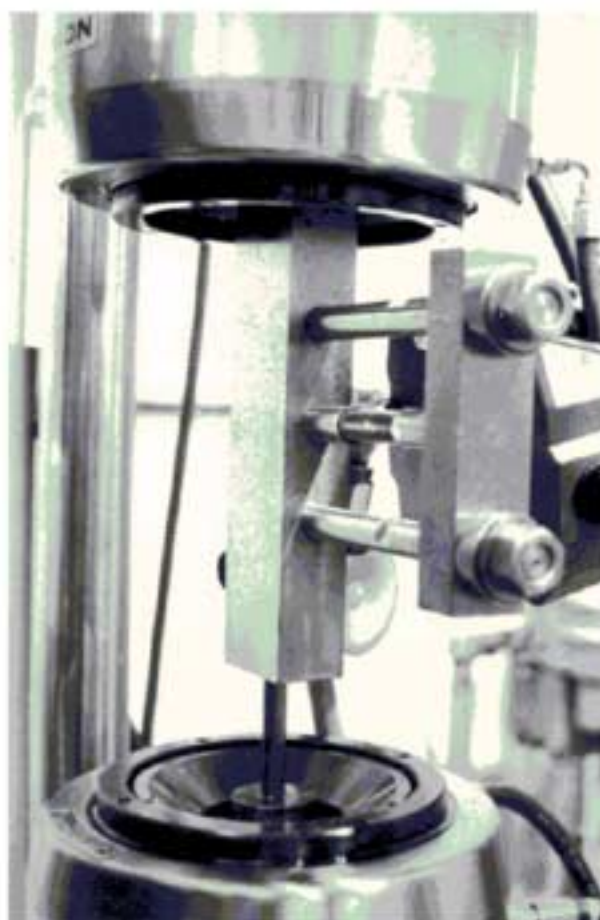


Figure4

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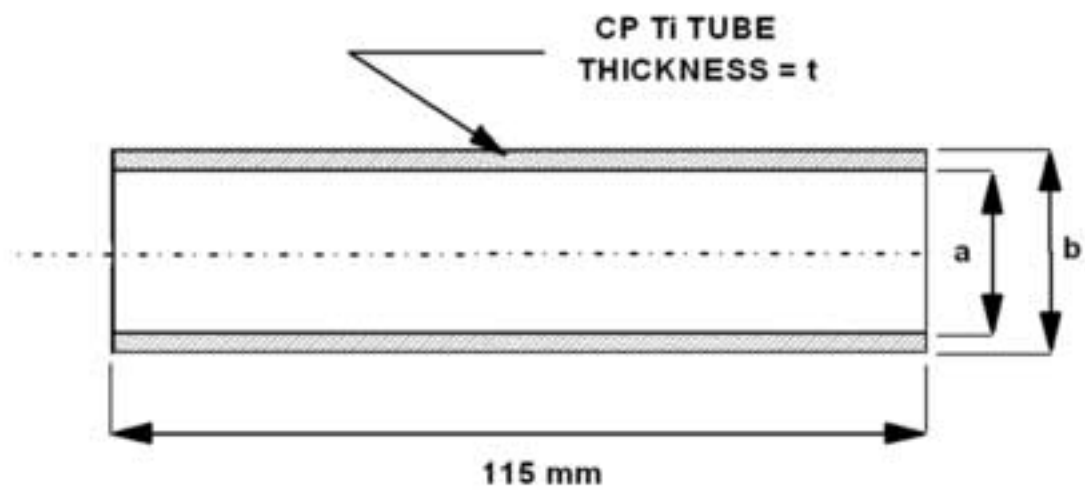


Figure5

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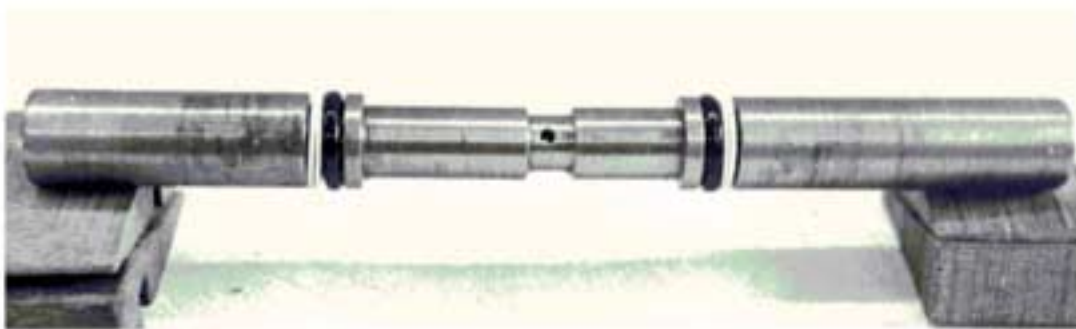
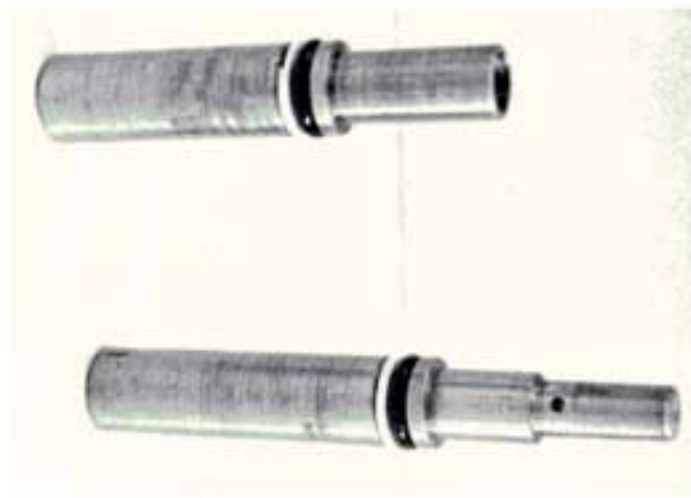


Figure6
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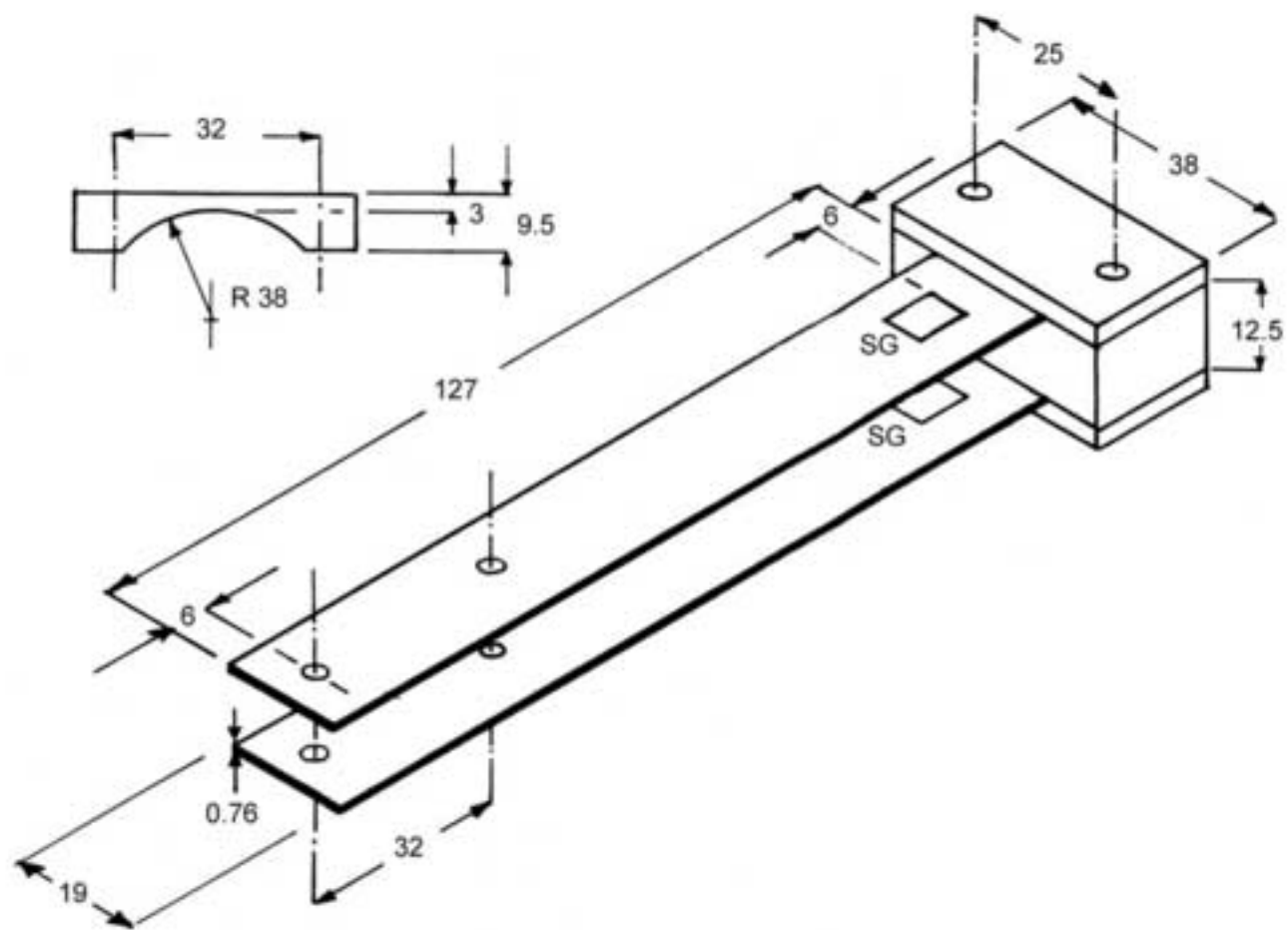


Figure7

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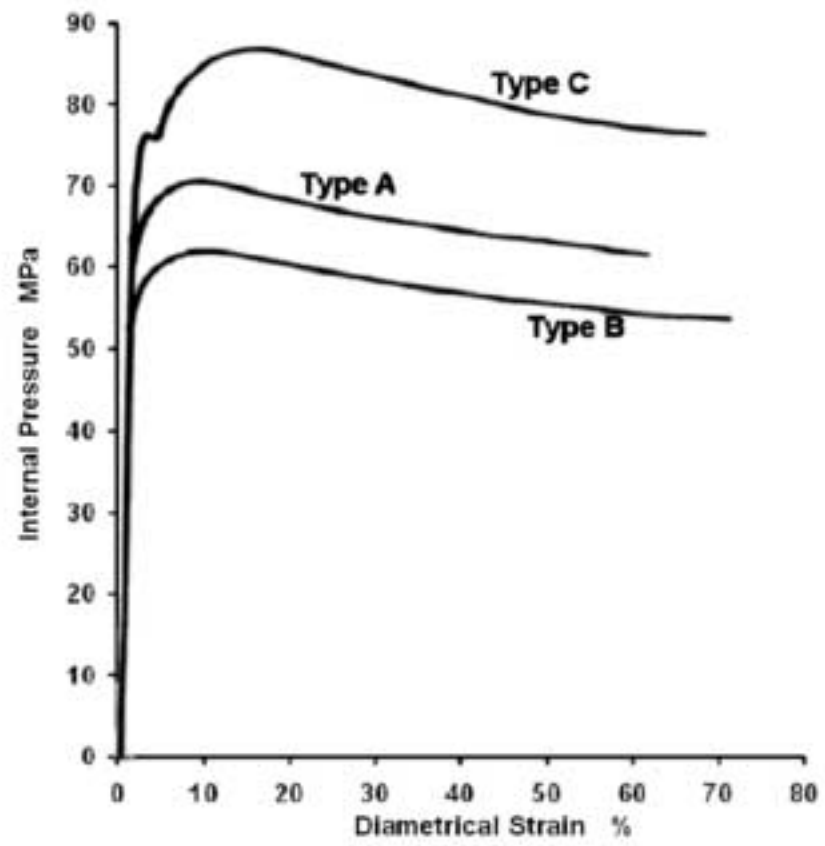


Figure8

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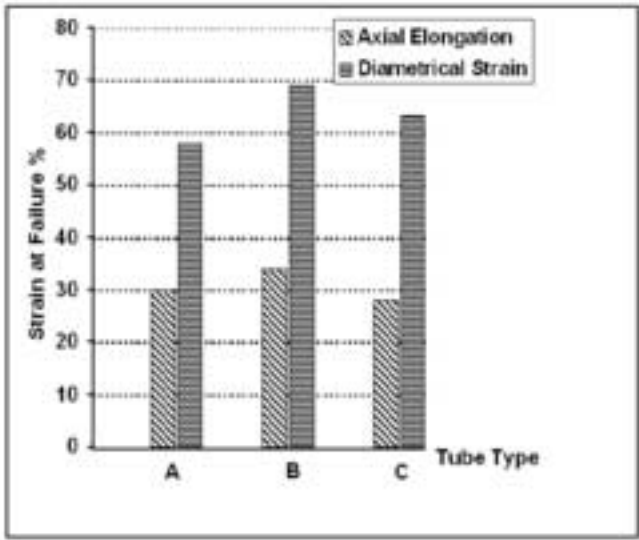
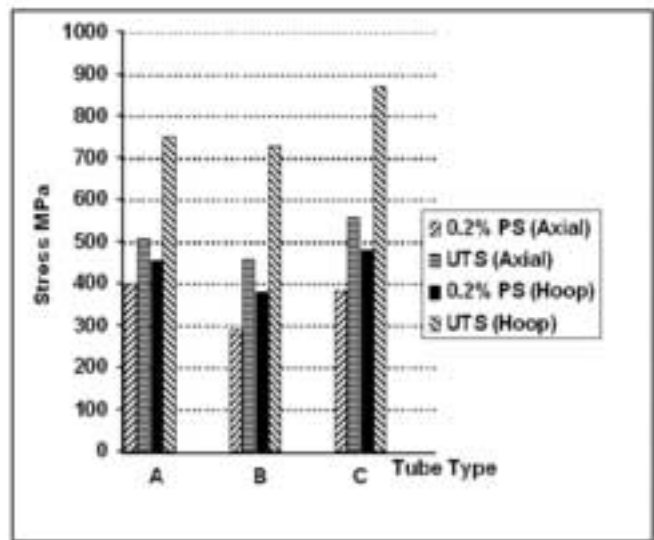


Figure9

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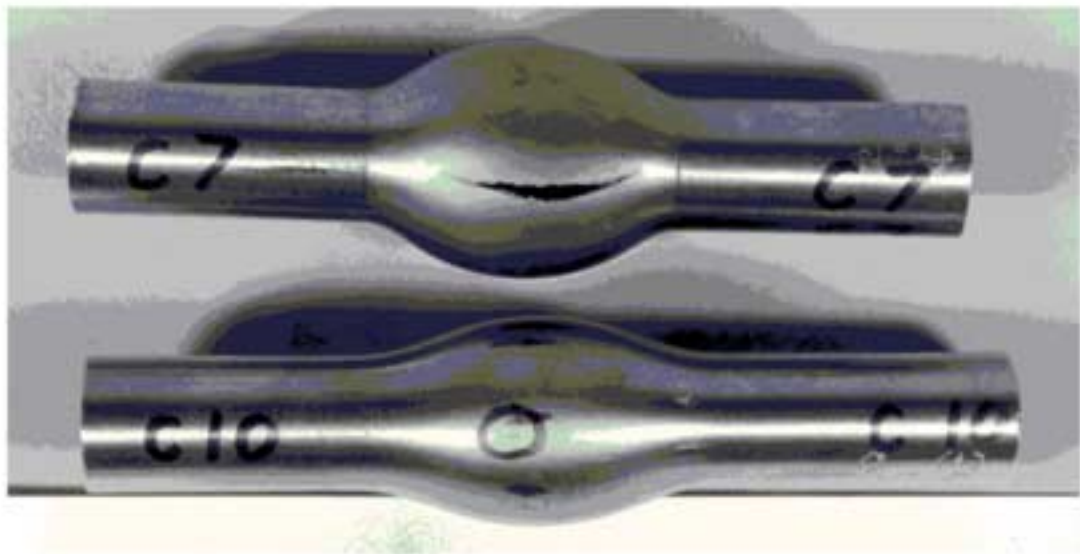


TABLE 1

Description of specimen tube types.

TUBE BATCH	INTERNAL DIAMETER 'a' mm	OUTSIDE DIAMETER 'b' mm	WALL THICKNESS 't' mm	OXYGEN CONTENT %
A (Vacuum annealed)	14.00	15.82	0.96	0.12
B	14.00	15.76	0.88	0.115
C	13.77	15.79	1.01	0.20

TABLE 2

Summary of results for tensile and circumferential loading tests (standard deviation in brackets).

TUBE BATCH	AXIAL LOADING CONFIGURATION			CIRCUMFERENTIAL LOADING CONFIGURATION		
	0.2% PROOF STRESS MPa	TENSILE STRENGTH MPa	ELONGATION %	0.2% PROOF STRESS MPa	CIRCUMFERENTIAL COMPONENT OF STRESS AT FAILURE MPa	DIAMETRICAL STRAIN %
A	400 (1.8)	506 (5.1)	30 (1.2)	454 (1.5)	748 (7.0)	58 (1.5)
B	289 (3.5)	455 (3.3)	34 (1.7)	379 (6.9)	727 (2.9)	69 (1.2)
C	383 (3.2)	559 (9.8)	28 (2.2)	478 (4.9)	870 (45.4)	63 (10.5)