Joining Methods Applied to Sintered Aluminium Products

Aastrup, P.; Moe, A.; Forskningscenter Risø, Roskilde

Publication date:
1966

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Aastrup, P., Moe, A., & Knudsen, P. (1966). Joining Methods Applied to Sintered Aluminium Products. (Denmark. Forskningscenter Risoe. Risoe-R; No. 145).

Risö Report No. 145

Risö Report No. 145

Danish Atomic Energy Commission

Research Establishment Risö

Joining Methods Applied to Sintered Aluminium Products

by P. Aastrup, A. Moe and P. Knudsen

October, 1966

Sales distributors: Jul. Gjellerup, 87, Sölvgade, Copenhagen K, Denmark
Available on exchange from: Library, Danish Atomic Energy Commission, Risö, Roskilde, Denmark

October, 1966 Risö Report No. 145

Joining Methods Applied to Sintered Aluminium Products

by

P. Aastrup

Danish Central Welding Institution, Copenhagen

and

A. Moe and P. Knudsen

The Danish Atomic Energy Commission
Research Establishment Risö
Metallurgy Department

Abstract

A major problem in the joining of dispersion-strengthened materials is to prevent destruction of the specific distribution of dispersed particles and thus avoid a decrease in high-temperature strength. The gas content may be another important factor since the presence of a large amount of gas in the material is likely to result in a porous welding zone.

Different welding methods applied to sintered aluminium products are reviewed. Experiments related to the flash welding process and certain types of fusion welding are treated in more detail.

SAP-SAP joints of satisfactory high-temperature strength and tightness have been made by flash welding. In the special versions of fusion welding, sound joints are obtained by using aluminium as filler material under closely controlled conditions. As a consequence, good joint strength and tightness at elevated temperatures are achieved also by these methods when a suitable joint design is used.

Presented at the Second Bolton Landing Conference, 27-29 June, 1966, in the Sagamore, Lake George, New York.

CONTENTS

1. INTRODUCTION

A major problem in the joining of dispersion-strengthened materials is to prevent destruction of the specific distribution of the dispersed phase and thus avoid a decrease in high-temperature strength. Gas content may be another important factor since the presence of a large amount of gas in the material is likely to result in a porous welding zone. Such considerations of course also apply to the joining of sintered aluminium products (SAP).

This paper presents experience from the development of joining methods for SAP, emphasizing aspects of importance for the application of the results to materials and geometries other than those investigated specifically.

First, reference is made to properties of SAP and characteristics of potential joining methods. Then follow results obtained by the flash welding process and by certain types of fusion welding, and an evaluation of the weldments, including characteristics of mechanical strength as well as structure and leak tightness. The merits of these processes are discussed in the final part of the paper.

2. MATERIAL CONSIDERATIONS

SAP consists of an alumina phase finely dispersed in aluminium, the oxide content being in the range of 4-15 weight per cent for most commercial materials.

An outstanding characteristic of these materials is their high strength at elevated temperatures as compared with that of conventional aluminium alloys.

The SAP materials are usually manufactured from aluminium powders ball-milled and simultaneously oxidized. The cold-compacted powder is vacuum-sintered and extruded into billets, which are finally shaped by extrusion, rolling, forging, etc. The vacuum sintering reduces the gas content below 10 ppm, which is considered acceptable for most applications1).

The extruded material has a directional structure. Accordingly, the mechanical properties are also directional; for instance, the transverse creep strength as measured in SAP 930 tubes exposed to internal pressure is only about 70% of the longitudinal creep strength2).

As regards the joining of SAP components, the selection of methods is restricted in comparison with the processes used for joining conventional aluminium alloys. As the distribution of the dispersed oxide phase must be maintained during joining in order not to lose the desirable high-temperature strength, joining should preferably take place in the solid state. This means that a feasible joining process will involve application of pressure and probably heat, which will cause the oxide skin of the mating surface to be broken and good metallic contact to be obtained.

However, with a close control of heat input it is possible to heat SAP to a temperature somewhat above the melting point of pure aluminium without impairing its structure unduly3). Therefore, fusion welding should not be entirely ruled out as a joining process.

The SAP materials used for the experiments reported in this paper are the commercial grades SAP 930, SAP 895 and SAP 865, having nominal oxide contents of 7, 10 and 13 weight per cent respectively. As-fabricated shapes include 16 mm rods from Swiss Aluminium and multifinned tubing (figure 1) manufactured by Imperial Metal Industries, England, for the cladding of nuclear fuel rods.

3. POTENTIAL JOINING METHODS

The various methods are grouped below according to the combination of materials in the joint.

Direct Joining of SAP to SAP

SAP-SAP joints can be obtained by the following processes, in which the material of the final joint has not been heated above the melting point of pure aluminium:

(a) Flash welding2, 4, 5, 6)
(b) Magnetic-force welding7)
(c) Friction welding8)
(d) Hot-pressure welding9)
(e) Cold-pressure welding6)
(f) Ultrasonic welding10).

The first four processes involve application of heat as well as pressure. In flash welding and magnetic-force welding the heat is generated in the joint region of the specimens by electric resistance heating, whilst in friction welding the heat is obtained mechanically by rubbing the joint faces against each other while applying pressure. Heating for hot-pressure welding normally involves preheating by means of an external heat source. In the case of flash welding and friction welding, melting of the mating faces occurs, but as the liquid material is squeezed away from the bonding zone during the final upsetting, bonding of the material in the solid state is obtained. Cold-pressure welding is carried out at room temperature and relies entirely upon pressure. Ultrasonic welding is a variant of cold-pressure welding in which ultrasonic vibrations, induced parallel to the joint faces, are used to break the oxide film, thus facilitating intimate contact between the mating faces.

All the above processes can be classified as pressure weldings. The applicability of a particular process depends upon the work pieces fulfilling certain geometrical requirements. Table 1 characterizes the various processes according to joint type and feasible specimen configurations.

Joining of SAP to SAP by Means of an Intermediate Layer

The eutectic bonding method involves the use of a thin intermediate layer of a metal forming a eutectic with aluminium, e.g. silver or silicon[6,11,12)]. The joint is formed by heating the combination of materials to a temperature slightly above the eutectic temperature while applying pressure. Detailed information about the strength of such bondings is not available, but it seems evident that sound and tight joints can be made.

Good joints have also been obtained with aluminium as the intermediate material[13)]. As in the eutectic bonding method, the components are pressed together and heated to a temperature below the melting point of aluminium. Thus no melting occurs, the bonding takes place completely in the solid state.

Conventional brazing processes have been applied to SAP with limited success because the brazing flux required to penetrate the surface oxide skin tends to damage the SAP structure.

Joining of SAP to Aluminium

The above processes can probably all be used for the joining of SAP to aluminium, provided the aluminium is not in too soft a condition to withstand pressure. In addition, fusion welding methods such as argon-arc[14,15)] and electron-beam welding[16)] can be applied. The SAP material must, however, have a low gas content to prevent the formation of porosities, and very close control of the whole welding cycle is required in order to avoid excessive heating of the SAP.

4. PRESSURE WELDING - FLASH WELDING

At the Research Establishment Risö of the Danish Atomic Energy Commission, investigations on flash welding of SAP have been carried out.

Flash Welding Experiments

With the parameters of table 2, 6 mm rods of SAP 930 and SAP 895 were welded and then machined to tensile testing specimens (see figure 2). These specimens were tested at temperatures ranging from room temperature to 630°C.

Flash welding was also applied to the end capping of the SAP 930 tubes shown in figure 1. The specimen geometry is illustrated by figure 3, and welding parameters are given in table 2. Note that upset material was removed outside, but not inside the tube prior to testing (figure 4). These end closures were burst tested at room temperature and 500°C, and also under creep conditions at 500°C. All end closures were helium leak tested prior to mechanical testing.

Typical longitudinal sections of flash-welded SAP 930 rod and tube material are shown in figures 5 and 6. The characteristic feature is that the macro-texture of the extruded structure is turned up to 90°. Thus the welding process does not destroy the dispersion as such, but it modifies the orientation of the structure.

The results of the tensile tests are presented in figures 7 and 8. For comparison, typical curves are included for as-delivered SAP 930 16 mm rod material. In SAP 930 the ultimate tensile strength of the weldments is about 90% of the longitudinal strength and higher than the transversal strength of the parent material. The ductility of the welded specimens is very low. This behaviour may be explained in part by the change in orientation of the structure, although influence from minor changes in the microstructure, and from microprocesses, cannot be excluded.

Burst testing of the welded tubes gave the results shown in table 3. These figures should be compared with the strengths measured for as-delivered tubing, also shown in table 3.

Thus, even in cases where welded tubes failed circumferentially in the weld, the rupture strength obtained was satisfactory compared with that of the non-welded tubes. This is presumably related to the fact that the weldments were not machined inside the tube, so that the upset material made the wall somewhat thicker at the joint.

Figure 9 shows the results obtained in creep burst testing at 500°C, including results for non-welded tubing for comparison.

The helium leak test showed a leakage rate not exceeding 3.5×10^{-6} lusec for any of the specimens, i.e. the flash-welded joints are "vacuum tight".

5. FUSION WELDING

At Risö, fusion welding has been applied to end capping of SAP tubes with Al-2S as filler material. The welding methods used were:

(1) TIG-welding with the arc rotated by a superimposed magnetic field, thus forming a cone. (TIG-welding is an electric-arc welding process in which a non-consumable tungsten electrode and an inert-gas shielding are used).

(2) MIG-welding by the short-arc technique. (This arc welding process works with a consumable metal electrode and an inert-gas shielding. The short-arc technique involves a low current intensity and a periodically short-circuiting electrode).

Geometrical changes observed on the welded thin-walled tubes have been further investigated by experiments on the effect of heat on SAP in the shape of thin-walled tubes and rods.

Main Features of Weld Performances

Normal TIG-welding of end closures on SAP tubes has been tried with only inferior results owing to poor heat control and deterioration of the SAP structure caused by the forces exerted by the arc.

The special version of TIG-welding characterized by a cone-shaped arc in combination with the end-plug design ensures controlled uniform heating of the specimens and limited action of the arc forces on the tube material. By nature this method is usable only on specimens with a circular cross section. The arrangement used for welding end closures on SAP tubes is sketched in figure 10. Two magnetic coils are placed along the same vertical axis, with north pole opposite south pole and at a distance of about 40 mm from each other. The tube specimen, fitted with a 2S-aluminium end plug at the top, midway between the coils, is mounted concentrically to the same axis. Just above the end plug a conventional TIG-welding gun is placed concentrically so as to give an arc gap of 5 mm. An arc struck between the tungsten electrode and the specimen will be affected by the magnetic field and deflected in such a way that it describes a cone with the top end at the electrode.

The end-plug design can be seen in figure 11, which shows a plug fitted to a tube end. Figure 12 shows a stage of the welding where the molten aluminium from the plug forms a hemisphere and thereby exposes the terminal surfaces of the tube to the action of the arc. An external view of an end closure on a multifinned SAP-tube is presented in figure 13.

The technique for making end closures by low-current MIG-welding is illustrated in figure 14. A 5 mm thick circular aluminium disc is inserted 5 mm into the tube. Welding is started on the outer surface of the end plug, and the cylindrical opening is filled by a circular movement of the welding gun, which is only slightly off-centre, so that only the tube wall surface is affected.

TIG-Welding Experiments

End closures of multifinned, thin-walled SAP tubes have been welded by the special version of TIG-welding under the conditions outlined in table 4. Both SAP 930 and SAP 865 tubes have been subjected to experiments, and no differences have been observed in the response to the welding process.

A number of end closures of SAP 930 tubes have been subjected to metallographic examination, pressure burst testing at room temperature and at 500°C, and pressure creep burst testing at 500°C.

A typical cross section of an end closure of a thin-walled SAP 930 tube appears in figure 15. The great enlargement shows that there is obviously a good metallurgical bonding between the aluminium and the face of the tube end. To a small extent bonding also occurs between the aluminium and the inside tube wall. Furthermore it is seen that a slight swelling can occur where bonding is obtained. It is likely that the aluminium matrix of the SAP material has been enriched by the molten aluminium of the end plug.

In figure 15 another geometric change of the tube wall can be observed in the form of a local thickening encircling the tube. Figure 16 illustrates that it is taking place at the same level as the transition zone in the aluminium plug between molten and unaffected material, and there seems to be a slight difference in the appearance of the microstructure of the SAP material on the two sides of the enlarged part. Some experiments made to further investigate this phenomenon will be discussed later in this section.

In pressure burst testing at room temperature, about 50% of the ruptures occurred in the end plug at pressures not quite satisfactory in comparison with the tube material. A typical rupture is presented in figure 17, where it is seen that it is the end-plug material which fails and not the bond between SAP and aluminium.

Pressure burst testing at 500°C showed rupture only in the tube material. This can possibly be explained by a mechanical bonding between end plug and tube wall owing to a greater thermal expansion of the plug material and a locking effect of the ring-shaped thickening of the tube wall.

Pressure creep burst testing resulted in end-plug failure in most cases.

These experiments show that a TIG-welded butt joint between SAP 930 and 2S-aluminium exhibits good strength in the bonding zone. However, in considering the process for constructional purposes, special care must be taken that the cross-sectional area of the aluminium component is of adequate dimensions. Figure 18 shows a longitudinal cross section of an end closure on tube material, designed in accordance with this principle to withstand for a long time the same internal pressure at 500°C as the SAP 930 tube material dealt with above. The tube dimensions are OD = 6.0 mm, ID = 1.2 mm. In figure 19, results of pressure creep testing at 500°C of such joints are graphed. A typical curve for creep-burst-tested SAP 930 multifinned tubing is shown for comparison.

MIG-Welding Experiments

The technique for making MIG-welded end closures on thin-walled SAP tube material has been investigated in a few experiments. Figure 20 shows a cross section of an end closure. It is obvious that bonding between the inside SAP tube wall and the deposited aluminium occurs over a considerably greater area than in TIG-welded end closures. However, the end closure displays a considerable degree of porosity, a problem well known in MIG-welding of aluminium.

Pressure burst testing at room temperature of eight MIG-welded and closures of multifinned SAP 930 tubes resulted in tube failures only.

Experiments on the Geometrical Change of SAP Material Exposed to Fusion Welding

In order further to illustrate the observed geometric change of thin-walled SAP tubes exposed to fusion welding, a few experiments involving heating of thin-walled SAP tubes and SAP rods have been carried out.

The tubes were exposed to the cone-shaped electric arc used for

TIG-welding of end closures. Instead of the aluminium end plug a 10 mm steel rod (which did not melt) was inserted in the tube. The response to this treatment was exactly the same ring-shaped thickening of the tube wall as that encountered in fusion welding. By X-ray diffraction it was observed that the texture of the aluminium matrix of the SAP had disappeared above the ring; it may thus be assumed that the matrix had been in a molten condition.

SAP rods, OD 11.3 mm, were heated in an electric furnace in a horizontal position to eliminate longitudinal influence of gravity on the molten aluminium matrix. The treatment was carried out in such a manner that a temperature gradient was obtained along the rod with the maximum temperature at one end. The rods showed an increase in thickness when heated to a sufficiently high temperature. Figure 21 illustrates a specimen after the experiment. The maximum increase in diameter obtained was about 30% of the original diameter. The temperatures at the points marked I and II in figure 21 were measured to be 647 and 656°C respectively. There is hardly any doubt that the material to the left of position II in the figure had been in a molten condition as the end of the rod was broken and a heavy radial shrinkage of the material, right up to position II, had taken place. By X-ray diffraction it was observed that the texture of the aluminium matrix in the zone between positions I and II was retained.

These experiments show that the thickening of SAP material observed in connection with fusion welding is not only related to welding, but can occur when SAP is heated to temperatures just below the melting point of pure aluminium. The phenomenon may possible be explained as an effect of thermal expansion properties of SAP materials as proposed in reference 17.

6. DISCUSSION AND CONCLUSIONS

With the same material and specimen configuration, the different pressure welding processes will all give much the same appearance of the zone adjacent to the bonding line. For example, pressure-welded thin-walled SAP tubes, when microsectioned, will be similar to figure 6. Consequently the mechanical properties of welds made by different pressure welding methods would be expected to be alike if the weldings had been carried out under optimum conditions. The results of the flash welding experiments presented here were not obtained under the very best conditions, but they have proved satisfactory for the purpose of SAP-UO_2 fuel-pin fabrication. The mechanical properties measured are probably indicative of what can be obtained in SAP welded by any pressure welding process: ultimate tensile strength a little lower than the longitudinal strength of the parent material (about 90% for SAP 930), but well over the transversal strength, and a relatively poor elongation. These properties call for special considerations in design, but should not eliminate pressure welding as a joining method for SAP materials.

Generally, the pressure welding processes may be considered effective joining methods, but the forces required for upsetting may in some cases give rise to complications in clamping. Eutectic bonding and diffusion bonding must be considered less effective joining processes.

Fusion welding can be used to join SAP and aluminium. With aluminium as filler material, TIG and MIG welding can probably also be used for joining SAP to SAP. In all cases success depends to a very great extent on close heat control and on an execution which prevents the forces exerted by the arc from being directed onto the SAP material. For practical purposes, attention must be paid to the inferior high-temperature strength of aluminium as compared with SAP. This necessitates particular emphasis on the design of the joint in order to keep stresses low in the aluminium part. However, the primary function of such a joint may be to provide tightness whilst a possible load is carried by other means. In fusion welding of SAP, swelling of the parent material can be expected around the fused zone.

ACKNOWLEDGEMENTS

The authors are very grateful to Mr. N. Hansen for helpful discussions and to the staff of the Metallurgy Department for their kind assistance.

REFERENCES

1) N. Hansen and E. Adolph, Risö Report No. 25 (1961).

2) Danish Atomic Energy Commission, Metallurgy Department, Annual Progress Report. Risö Report No. 110 (1965) 53 pp.

3) C. L. Meyers and O. D. Sherby, J. Inst. Metals 90, 380-382 (1961-62).

4) Bridoux, Kaufman, Thome, and Foulquier, Nucl. Eng. 6, 189-192 (1961).

5) E. G. Nelson and R. J. Towner, Welding J. 41, 89-s-92-s (1962).

6) E. C. Supan, W. H. Friske and G. V. Alm, NAA-SR-8578 (1963) 23 pp.

7) L. E. Mills, H. W. -72379 (1962) 23 pp.

8) E. A. Taylor, P. R. Pomeroy and K. F. Layland, Welding and Metal Fabrication 30, 477-481 (1962).

9) K. H. Wollaston, Welding and Metal Fabrication 30, 319-323 (1962).

10) R. Akeret, J. Nucl. Mat. 8, 126-137 (1963).

11) Kendall, Alm, Friske, Brinstock, Briggs, and Gradle, NAA-SR-6213, 13-17 (1961).

12) N. Hansen, E. Adolph and J. Christensen, Risö Report No. 13 (1960).

13) R. C. Hallam and W. J. Burns, The Canadian Mining and Metallurgical, 332-337 (1965).

14) G. D. Nikoforov and C. N. Zhiznyakov, Svar. Proiz. (Welding Production) No. 6, 1-4 (1964).

15) Hansen, Knudsen, Winther, and Adolph, Third United Nations International Conference on the Peaceful Uses of Atomic Energy, A/CONF. 28/P/421, September 1964.

16) Meulemans, Tytgat, van Audenhove, Briola, and Jehenson, EUR 39. e. (1962).

17) Meyers Jr., L. Charles, Shyne, C. John, and Oleg D. Sherby, United States Goverment Research Report AD-292061 (1962).

Table 1

Characteristics of Pressure Welding Processes According to Joint Type and Feasible Specimen Configuration

Welding method	Joint type	Feasible-specimen configuration
Flash welding	Butt	Rod, tube and other sections
Magnetic-force welding	Butt	Rod, tube and other sections
Friction welding	Butt	Cylindrical sections as rod and tube
Hot-pressure welding	Butt and lap	Any configuration where pressure can be applied
Cold-pressure welding	Butt and lap	Any configuration where pressure can be applied
Ultrasonic welding	Lap	Maximum thickness about 1 mm

Table 2

Parameters for Flash Welding of SAP Rod and Tube Materials

Material	6 mm rod SAP 930 or SAP 895	End cap on 24-finned SAP 930 tube
Voltage	3.1 volts	3.1 volts
Flashing velocity	5.2 mm/sec	3.5 mm/sec
Flashing length	8.0 mm	5.0 mm
Upsetting length	5.0 mm	3.0 mm
Upsetting force	800 kg	550 kg
Current time during upsetting	2 cycles (1/25 sec)	2 cycles (1/25 sec)

Table 3

Results of Burst Tests on Flash-Welded and As-Delivered 24-Finned SAP 930 Tubes
Test temperatures: 20 and 500°C

Condition of the 24-finned SAP-930 tube material	Flash welded		As-delivered	
Temperature, °C	20°	500°	20°	500°
Burst pressure, kg/mm^2	3.46	0.76	3.49	0.75
Standard deviation, kg/mm^2	0.05	0.02	0.08	0.04
Total number of tests	14	9	58	19
Number of complete or partial failures of the weld	7	3		

Table 4

Conditions for Magnetic-Field-Influenced TIG-Welding of Multifinned Tubes

Tungsten-electrode diameter		4 mm
Distance from electrode to work piece		5 mm
Current-time cycle:	Up-slope	1.5 sec
	Hold 70 A DC rev. polarity	3.5 sec
	Down-slope	1.5 sec
Argon flow		10 l/min
Number of turns per coil		750
Coil current		0.6 A
Coil polarity		Same for both coils
Distance between coils		40 mm

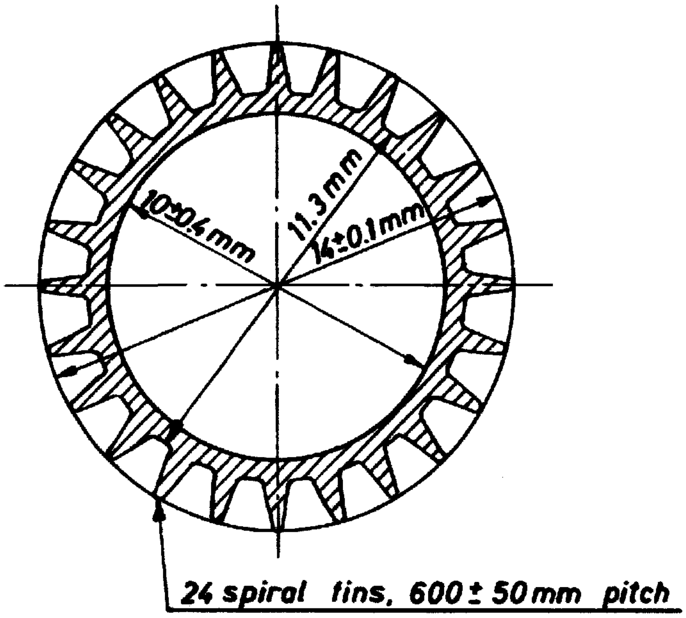
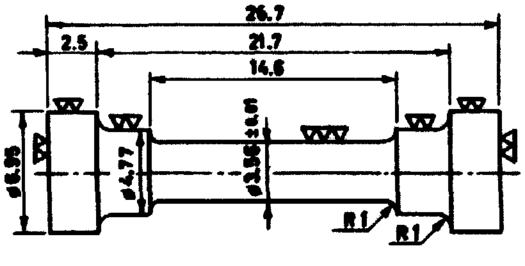


Fig. 1. Cross section of multifinned SAP canning tube.



Dimensions in mm

Fig. 2. Tensile test specimen (type Houldcroft) machined from flash-welded 6 mm rods of SAP 930 or SAP 895. The bonding zone is at the middle of the specimen, perpendicular to the axis.

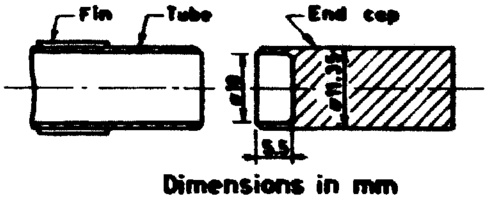


Fig. 3. Geometry of components used for end capping multifinned SAP 930 tube by flash welding.

Fig. 4. Flash-welded, multifinned SAP 930 tube prior to pressure burst testing. Outside upset material removed.

Fig. 5. Longitudinal section of flash-welded SAP 930, 6 mm rod material. x 23 and x 550.

Fig. 6. Longitudinal section of flash-welded SAP 930 multifinned tube. x 27 and x 600.

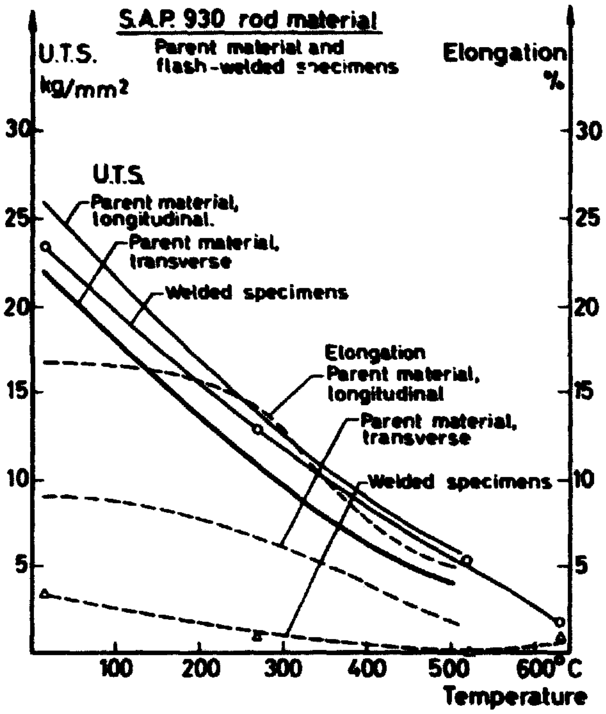


Fig. 7. Ultimate tensile strength and total elongation versus temperature as measured for flash-welded SAP 930 6 mm rod material. Each point represents the mean of four measurements. Typical curves of longitudinal and transverse U. T. S. and total elongation for the parent 16 mm rod material included.

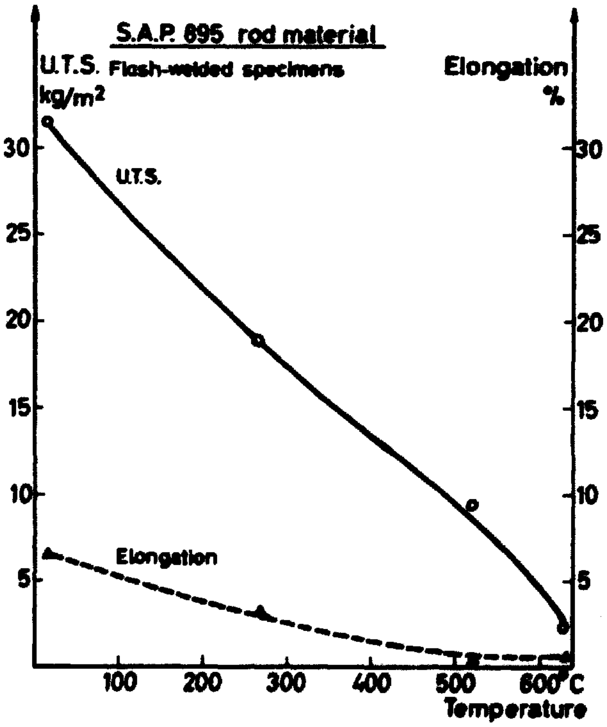


Fig. 8. Ultimate tensile strength and total elongation versus temperature as measured for flash-welded SAP 895 6 mm rod material. Each point represents the mean of four measurements.

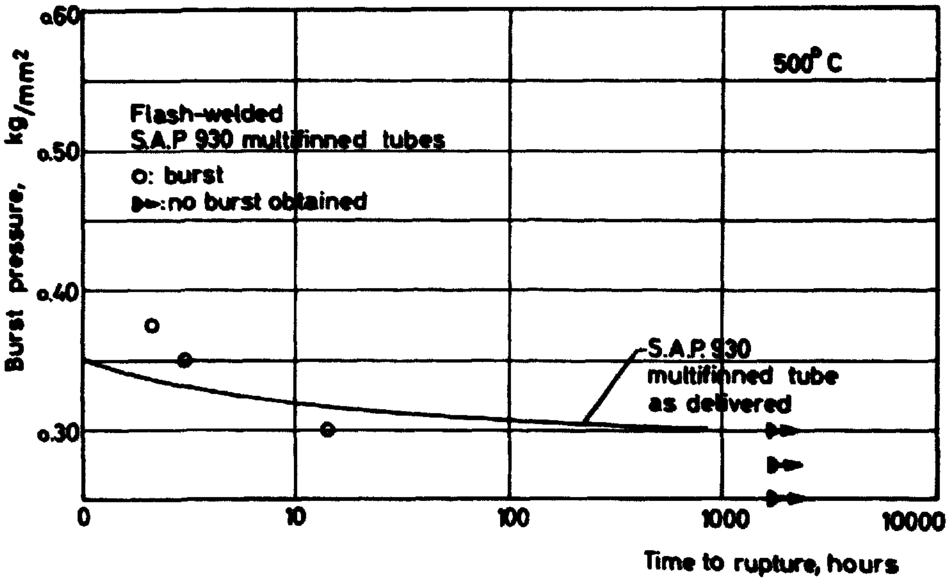


Fig. 9. Results obtained from creep burst testing at 500°C of flash-welded multifinned SAP 930 tubes. Typical curve for as-delivered multifinned SAP 930 tube included.

Fig. 10. Arrangement for TIG-welding with the arc rotated by a superimposed magnetic field.

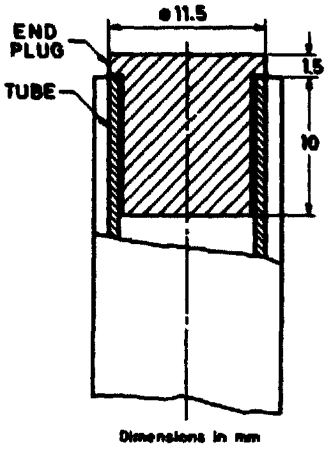


Fig. 11. Aluminium end plug fitted to multifinned SAP tube. Ready for TIG-welding.

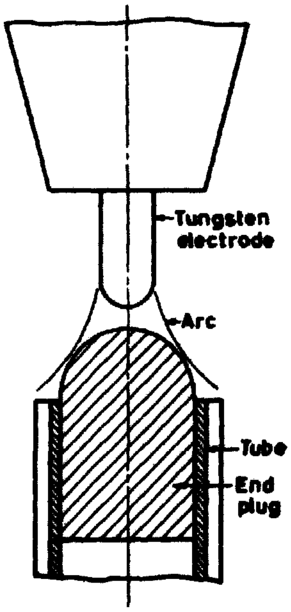


Fig. 12. Stage during TIG-welding with cone-shaped arc of an aluminium end plug to multifinned SAP tube, the molten plug material forming a hemisphere.

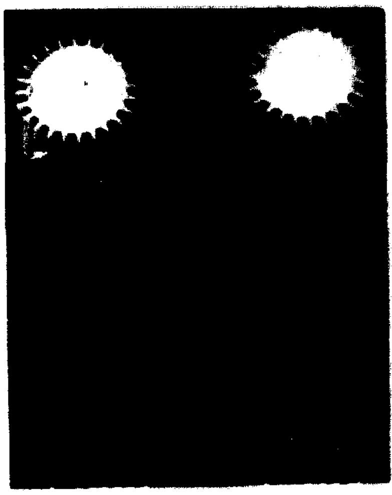


Fig. 13. External view of aluminium end plug TIG-welded to multifinned SAP tube.

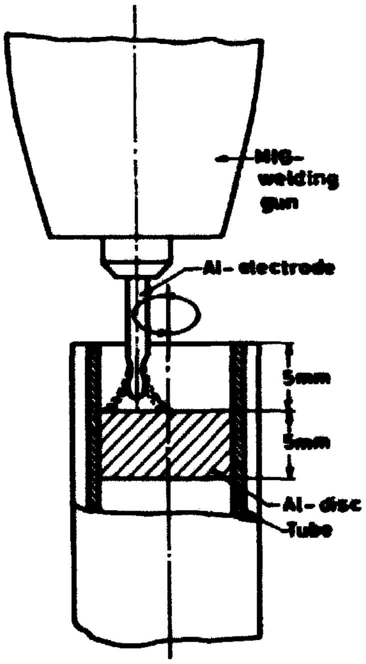


Fig. 14. Arrangement for making end closure of multifinned SAP tube by low-current MIG-welding.

Fig. 15. Longitudinal cross section of end closure made by TIG-welding aluminium plug to multifinned SAP 930 tube. x 18 and x 800.

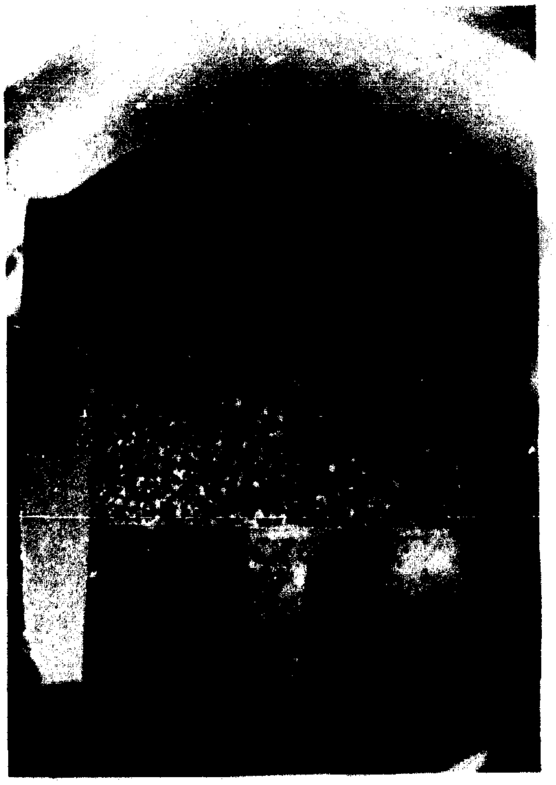


Fig. 16. Macrostructure of TIG-welded Al-SAP tube end closure. Local thickening of the tube wall has taken place at the same level as the transition zone between molten and unaffected plug material. x 5.

Fig. 17. Typical rupture in aluminium end cap on SAP tube after pressure burst testing at room temperature. x 18.

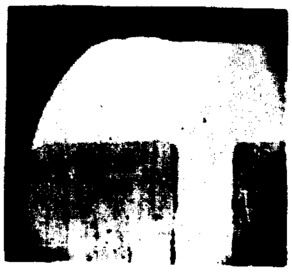


Fig. 18. Longitudinal cross section of end closure made by TIG-welding aluminium plug to thick-walled SAP 930 tube. OD = 6.0 mm, ID = 1.2 mm. x 18.

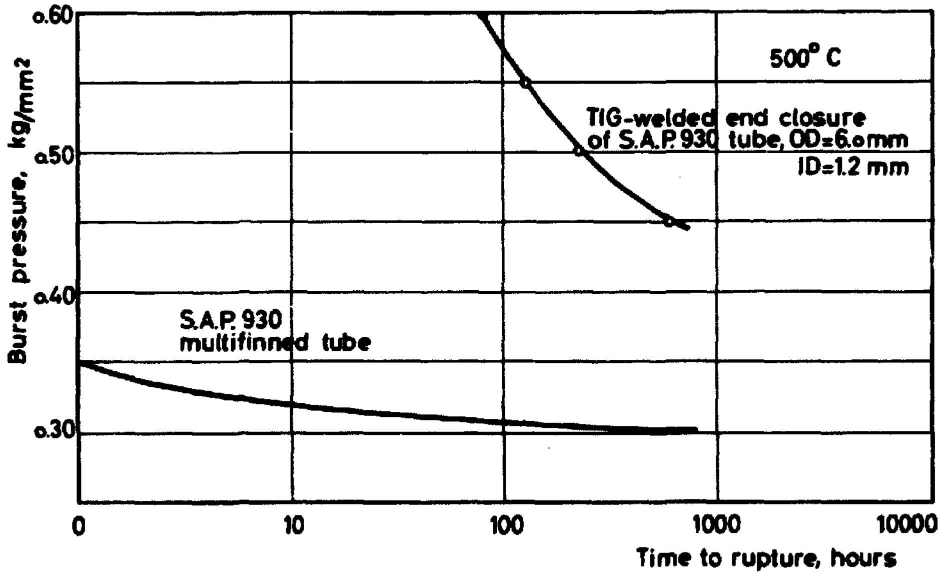


Fig. 19. Results obtained in creep burst testing at 500°C of TIG-welded end closures on thick-walled SAP 930 tube. OD = 6.0 mm, ID = 1.2 mm. Typical curve for creep-burst-tested SAP 930 multifinned tube included.

Fig. 20. Typical cross section of MIG-welded end closure of multifinned SAP tube. x 30.

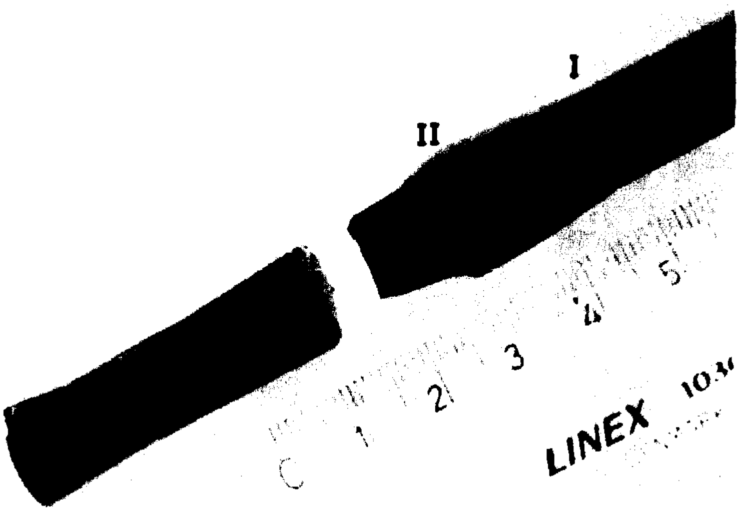


Fig. 21. 11.3 mm SAP rod heated in a horizontally positioned electric furnace giving a temperature gradient along the rod. Temperatures registered: $T_I = 647^\circ C$, $T_{II} = 656^\circ C$.