RECLAMATION OF PROPELLER SHAFTS

BY SUBMERGED ARC WELDING

BY

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Damage to tail shafts is usually caused by corrosion, accelerated galvanically at the junctions of the shaft with non-ferrous metals. It can also be caused by deep grooving formed from the abrasive action of the packing used in watertight glands, or in way of lignum vitae bushes fitted in the eddy plates and fairing plates.

It is now standard practice to protect the exposed portions of the shaft by wrapping them with fibre-glass tape which is then impregnated with epoxy resin, a technique found to be effective in eliminating corrosion damage. Pitting can still occur on the journal or bearing surface in way of the stern tube due to the ingress of sea water, and the journals can become worn or oval. It is with the reclamation of such journals that this article is primarily concerned.

Tail shafts may be up to 18 in. diameter and 80 ft long, with a journal length of 6-30 ft. The majority are hollow, with wall thicknesses of 1-3 in., but many of the smaller shafts are of solid section. The materials are generally plain carbon steels within the 28-32 T.S.I. or 34-38 T.S.I. ranges, with carbon contents of 0·2-0·4 per cent and manganese up to 1·5 per cent.

Shafts are designed with a generous safety factor, and, within specified limits, pitted journals may be machined down to a sound surface and oversize bearings fitted. This was originally the only way in which the life of a shaft could be prolonged, and when the minimum permitted diameter was reached, replacement became necessary.

The Early Attempts at Repair by Welding

The first recorded attempts at the repair of shafts by welding were to the destroyer H.M.S. *Wishart* at Shanghai in 1932 and the submarine L20 at Portsmouth in 1933. An investigation into the electric arc welding of propeller shafts was carried out by the Admiralty Engineering Laboratory in 1934, and from then until 1944 an increasing amount of this welding was carried out in home and overseas dockyards, often using electrodes which have long since been superseded in the welding world. Towards the end of the war consideration was given to reclamation by metal spraying; but this was not pursued, and in 1945 an Admiralty Fleet Order was issued recommending a suitable welding technique. In November 1944 a report (1) was issued by the Central Metallurgical Laboratory regarding welding trials with a submerged arc machine in which it was suggested that the process might well be adopted for shaft reclamation. Comparative trials on an experimental shaft were ultimately completed, and the results showed that the automatically welded sample was metallographically sound and had a lower level of surface tensile stress. In 1953 instructions were issued to dockyards on shaft reclamation by submerged and

TABLE I—*Chemical Composition of Shaft and Filler Wire*

	Carbon	*Silicon*	*Manganese*	*Phosphorus*	*Sulphur*	*Nickel*	*Chromium*	*Copper*
Shaft	0·37	0·21	0·75	0·045	0·033	0·20	0·11	0·05
Wire	0·13	0·14	1·90	0·019	0·017	0·10	0·10	0·10

metal arc processes specifying the details of shaft preparation, electrode or filler wire to be used, preheat, welding sequence and post-weld inspection.

Additional work (2) was reported in 1953 in which it was shown that surface tensile stresses could be relieved by stress relieving at 650 degrees C and altered to compression by cold rolling. This work was followed by a series (3) of corrosion fatigue trials in sea water in which stress/endurance curves were determined for mild steel and a number of welded specimens. The welded specimens were prepared using various metal arc welding electrodes and automatic processes, and were tested in the as-welded, heat-treated and cold-rolled conditions. The results showed that a reduction in corrosion fatigue life occurred when a shaft was repaired by welding but that the reduction was least when automatic welding was used. Post-weld stress relief and cold rolling were beneficial.

In 1956 a serious case (4) of hot cracking on a welded tail shaft was experienced at Portsmouth and, since this followed an earlier and similar example at another dockyard, an investigation was put in hand. The cracking was found to be due to a high sulphur content in the parent shaft coupled with the use of a flux which gave a low manganese recovery. Substitution of a flux rich in manganese, which ensured a manganese/sulphur ratio of at least 25 : 1 in the weld metal, effectively eliminated the trouble.

About the same time concern was caused in Devonport Dockyard when it was found that a submarine shaft which had been reclaimed by welding had undergone a longitudinal contraction of 1¼ in. and could not be replaced in service before further modifications had been made. Trials (5) duplicating the welding conditions showed that the phenomenon was genuine and repeatable, and, as a precautionary measure, current limitation was advised when welding thin-walled shafts.

The results of all experimental work were issued to dockyards in 1957 superseding earlier instructions.

A further outbreak of hot cracking was reported at Portsmouth in 1960, and this was traced to the use of high welding currents employed in an attempt to increase the turn-round time of worn shafts. Cracking was eliminated when the current was reduced to its former value.

The possibility of increasing output by the use of modified submerged arc processes (6-8), including twin-arc, series-arc and circumferential welding, was then considered. It became apparent during trials that considerable development work would be required before such processes could be applied to shaft reinforcement. It was then found that welds could be laid by means of a conventional welding head in longer lengths than had hitherto been attempted without a significant increase in distortion. Previously a journal was divided into equal lengths of 2-3 ft long and alternate lengths were welded. The shaft was then returned to the lathe for intermediate straightening and machining. Next it would be returned to the welding bay for the remaining lengths to be welded and again returned to the lathe for final straightening and machining. The results (9) of the 'increased length' trials were encouraging and were extended until journals up to 12 ft long were welded by full length longitudinal deposition,

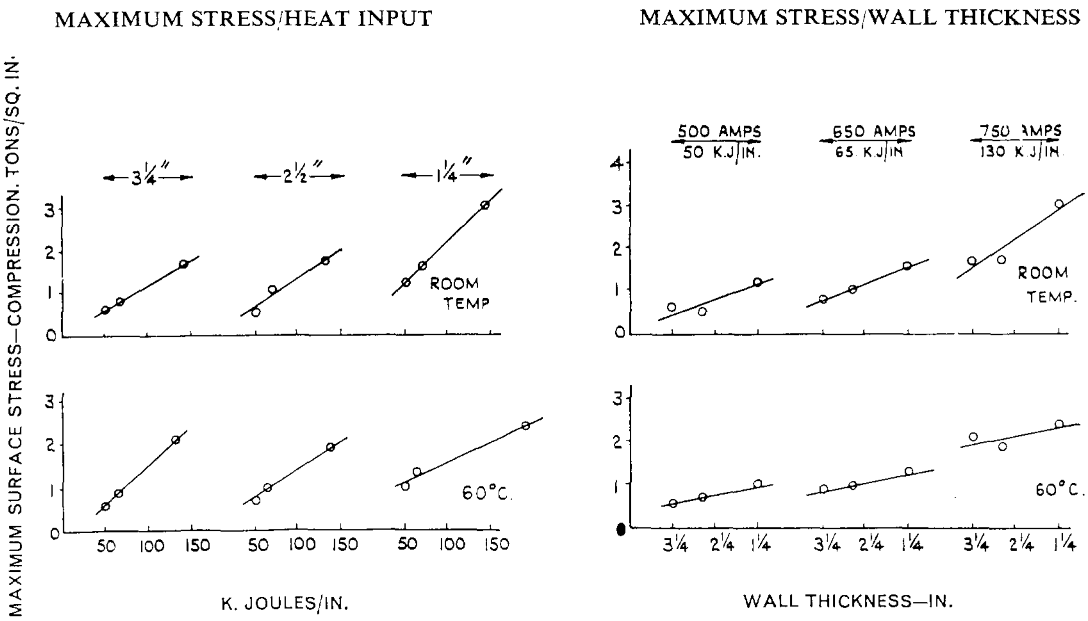

FIG. 1—GRAPHS INDICATING MAXIMUM SURFACE STRESS DEVELOPED AND VARIABLES OF HEAT INPUT, PREHEAT AND SHAFT WALL THICKNESS

sometimes three complete layers high, without any intermediate straightening or machining.

To place the proposed new techniques on a sound basis it was decided to investigate the relationship between hot cracking, in terms of surface tensile stress developed during welding, and such variables as heat input, preheat and shaft wall thickness, and to obtain information on the control of distortion and shortening of shafts together with the relevant chemistry of weld deposits. From this and earlier work it was proposed to issue a comprehensive report (10).

Variables Affecting Surface Stress

The investigation was carried out on a 6 ft length of shafting which had been machined at the bore to give three 2 ft sections having wall thicknesses of $1\frac{1}{4}$ in., $2\frac{1}{2}$ in. and $3\frac{1}{4}$ in. respectively.

The strain gauges were Tinsley 6K, which were cemented to the shaft with 'Durofix' after preliminary tests had shown the bond to be stable up to approximately 100 degrees C. Compensating gauges were cemented similarly to steel blocks, shaped and lapped to the contour of the shaft. The fixed thermocouples (iron/constantan) were inserted in holes drilled in the shaft to two-thirds the respective wall thickness, while the couples (iron/constantan) used for measuring bore temperatures were movable and were held in the desired position immediately beneath individual weld runs magnetically, with couple beads in contact with the bore of the shaft.

All welding was carried out using $\frac{1}{4}$ in. diameter 2 per cent manganese wire and a high manganese type flux with an arc travel speed of 10 in. per minute. Three levels of heat input and three levels of preheat were employed. Sufficient time was allowed to elapse between individual test runs for shaft temperatures to be re-established at the desired limits and for transient stress to disappear.

The chemical composition of shaft and filler wire are given in TABLE I. The relationship between maximum surface stress developed and the variables of heat input, preheat and shaft wall thickness are shown graphically in FIG. 1. Two levels of preheat only are plotted, as results with a preheat of 100 degrees C

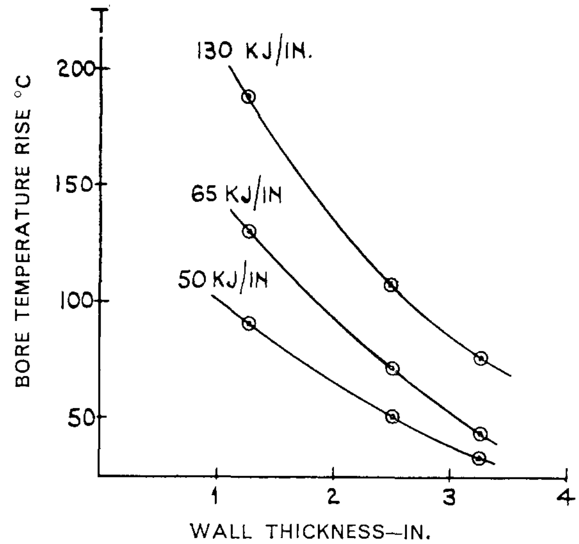

FIG. 2—RISE IN BORE TEMPERATURE WITH INCREASING WALL THICKNESS FOR VARIOUS HEAT INPUTS

were unreliable due to the suspected failure of the bond between gauge and shaft. The term 'maximum surface stress' was given to the highest stress recorded at the fixed strain gauge position during the respective welding sequence, and values represent the change in stress at a point with respect to the different welding variables: it follows that the higher the stress recorded at this point the higher the tensile stress developed in the weld, though not necessarily at the same instant of time. Heat inputs were recorded as kilojoules/in. according to the equation:

$$\text{Heat input} = \frac{\text{Amps} \times \text{volts} \times \text{power factor} \times \text{seconds}}{1000 \times \text{weld length}}$$

The rise in bore temperatures recorded by the movable couples immediately beneath the weld bead are shown in FIG. 2 as a function of heat input and shaft wall thickness. Fixed thermocouples did not provide reliable data, due to their varying position relative to the weld bead. No hot cracking was observed in any of these trials.

The results confirmed previous ideas that stress increased directly with heat input and inversely with wall thickness within the limits examined. The effect of preheat was less clearly defined, but it appeared to have little effect on stress levels when shaft wall thicknesses were equal to or exceeded $2\frac{1}{2}$ in. Preheat caused a significant reduction in stress levels only when the thin-walled section was welded using the highest heat input.

The temperature measurements showed that shaft bore temperatures did not nearly approach the values previously supposed. The rise in temperature immediately beneath the weld bead did not exceed 200 degrees C when welding on the thinnest shaft wall with the highest heat input and was only 70 degrees C when the $2\frac{1}{2}$ in. wall was welded with a heat input of 65 kJ/in.

It was thought that bore temperatures had a marked influence on shaft shortening and shaft distortion, and accordingly further measurements to determine the rise in bore temperature of production shafts were considered desirable.

Permanent Contraction of Shafts

Measurements of shafts before and after welding showed that virtually all shafts underwent a permanent contraction to some degree, irrespective of wall thickness and heat input.

Of the physical factors responsible, it was thought that the rise in bore temperatures appeared to be the most relevant, and in the case of the thinnest-walled shafts at present in service and within the levels of heat input examined, experiments showed that the rise was unlikely to exceed 250 degrees C during a working day. A further factor which has to be considered is the bowing of a shaft which occurs during welding, particularly the condition represented by the

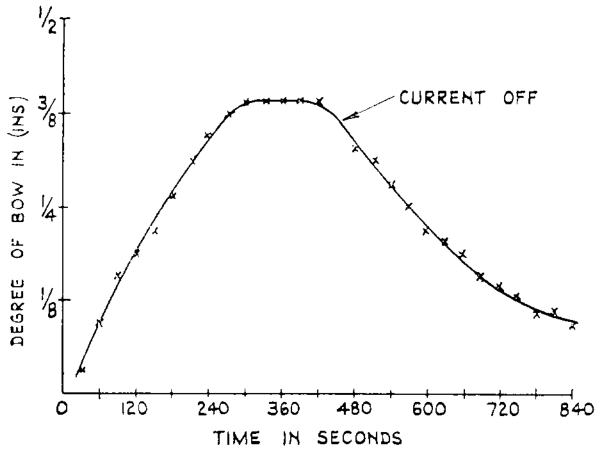

FIG. 3—DEGREE OF SHAFT BOW MEASURED DURING A SINGLE WELD BEAD AT A POINT MIDWAY ALONG THE JOURNAL

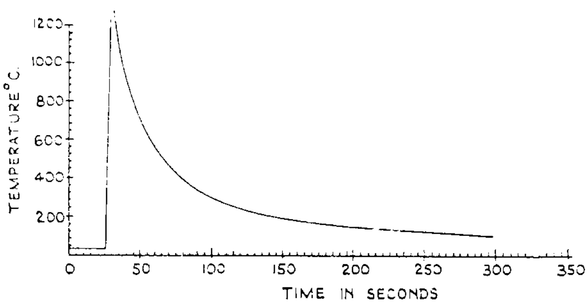

FIG. 4—COOLING CURVE OF WELD BEAD

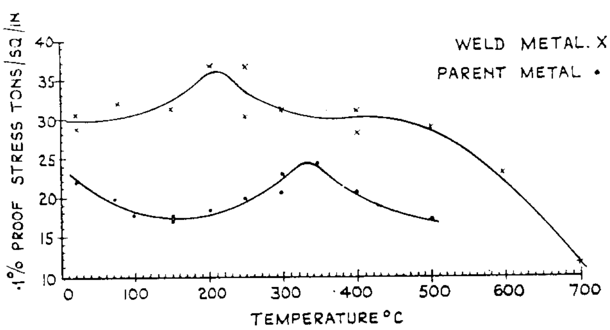

FIG. 5—1 PER CENT PROOF STRESS/TEMPERATURE

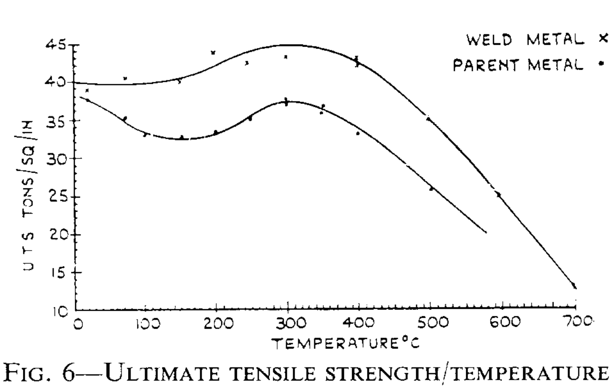

FIG. 6—ULTIMATE TENSILE STRENGTH/TEMPERATURE

flat portion of the curve shown in FIG. 3. This illustrates the extent of the bowing which was measured during the deposition of a single weld.

Metallurgical factors comprise the cooling rate of a production weld bead shown in FIG. 4, and the variation with temperature of the mechanical properties of both parent and weld metal. The latter, shown in FIGS. 5 and 6, clearly indicate that the weld deposit retained a high yield point up to 500 degrees C and that over the temperature range examined, weld yield strength was always significantly greater than that of the parent metal.

It is clear that all these factors are of importance when considering the shortening of shafts during reinforcement welding, since a considerable thermal gradient exists across the shaft wall, with a consequent significant variation in yield strengths. With these points in mind the following theory is advanced to explain shaft contraction. The individual 'stages' referred to are arbitrary, and for reasons of simplicity, consideration is restricted to a single run deposit.

Stage 1

The weld deposit cools rapidly to, say, 750 degrees C. The rigidity of the colder shaft metal prevents linear contraction and the resultant stresses are relieved by plastic flow in the weld.

Stage 2

The adjacent metal layer receives conducted heat and tends to expand but is partially or wholly restrained by the colder layers towards the bore not yet expanding or expanding at slower rates. Expansion stresses in this layer will be partly relieved by plastic flow (upsetting) in a radial direction.

Stage 3

The metal towards the bore of the shaft begins to expand but is restrained by the remaining mass of shaft, as yet unaffected by the heat of welding. As these expansion stresses become paramount, bowing of the shafts occurs with the weld uppermost, causing further plastic flow in the weld.

Stage 4

The contraction stresses in the outer layers of metal, whose yield strength is rising, are now comparable to the expansion stresses of the metal at the bore, whose yield strength has fallen with rising temperature. Some relief of the expansion stresses of the bore metal is now achieved by radial plastic flow (upsetting), but as the contraction stresses in the outer layers become paramount the bow in the shaft is reduced.

Stage 5

Thermal equilibrium is now reached, but because of radial upset the increase in shaft length is not proportional to the rise in shaft temperature. When the shaft cools, unrestrained contraction takes place along all the major axes. The shaft will therefore have undergone a permanent contraction, the extent of which will be a function of the linear restraint developed during expansion cycles.

The Mechanism and Effectiveness of Thermal Straightening

It is intended to give only a brief description of the process, since adequate coverage has been given elsewhere (11) (12), but the similarity of the mechanism to that resulting in permanent contraction will be apparent. The method of straightening is to apply localized heating to the convex side of the distorted shaft at the point of maximum eccentricity. The heated metal expands but is restrained by the rigidity of the surrounding cold metal in all but a radial direction. The expansion stresses cause the initial distortion to increase, but simultaneously the yield strength of the heated area is reduced and some plastic upsetting occurs, i.e. the shaft increases in thickness. When cooling occurs, unrestrained contraction results in shortening of the convex side, with a consequent tendency for the shaft to straighten.

Consideration of this mechanism shows that maximum response will be obtained with metals that have low thermal conductivity and high thermal expansion, and whose yield strengths fall off rapidly with increase in temperature. Residual compressive stresses along the convex edge will increase and tensile stresses reduce the effectiveness of the mechanism.

Recent experience had shown it extremely difficult to straighten shafts thermally by siting the heat on the weld metal, and rather than resort to mechanical methods it was decided to heat-treat the welded portion of the shafts in question. Since it was considered that the high yield point of the as-deposited weld metal was the most significant feature, the welded portions of the shafts were furnace heated to 870 degrees C. Supports were used as necessary and were so placed in the region of eccentricity that the shafts would tend to straighten under their own weight. The shafts were allowed to cool *in situ*.

The response to thermal straightening following this treatment was most satisfactory, and the residual eccentricity in two shafts so treated was reduced to within rough machining limits without difficulty. Further, since the furnace treatment had also relieved the residual stress in the shaft, no 'movement' was experienced as machining progressed.

The Chemistry of the Process

Five submerged arc fluxes and four filler wires were chemically examined together with individual layers of multi-layer deposits up to three layers high,

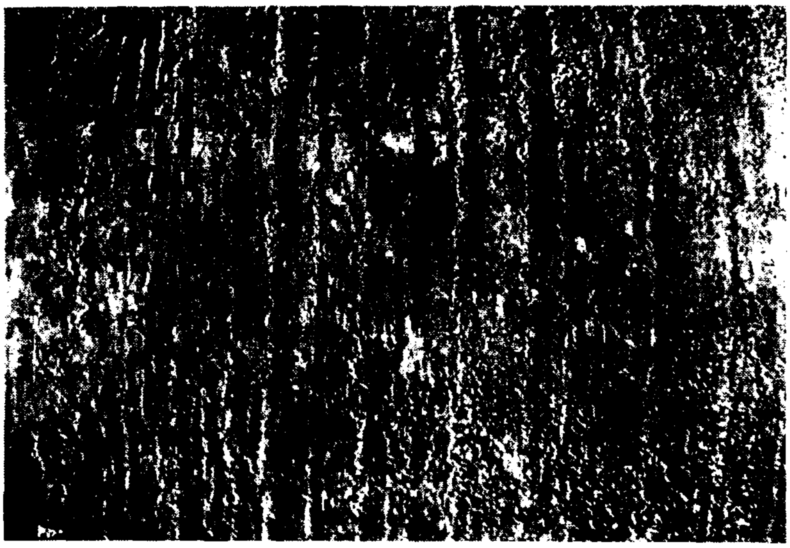

FIG. 7—A TYPICAL PART OF THE SURFACE OF A SCORED AND CORRODED JOURNAL BEFORE RECLAMATION

using various combinations of flux and filler wire. The results showed that in order to achieve a minimum manganese/sulphur ratio of 25 : 1 it would be necessary to use a $1\frac{1}{2}$-2 per cent manganese wire in conjunction with a high-manganese flux. It was further established that the use of such filler wire/flux combinations did not result in an unduly high manganese content in the second and third layers and that, since the carbon content in these layers had fallen, the carbon equivalent was actually less than that of the parent metal.

Factors Affecting Economical Shaft Reinforcement

The main requirement for Admiralty dockyards has always been to ensure a high-class reinforcement consistent with economical production and freedom from any chance of cracking during welding. In the past, the accent was placed on freedom from hot cracking coupled with the minimum of distortion. The production of reclaimed shafts had always suffered from down-time of the welding head due to:

(1) The time required to heat the shaft to the preheating temperature (85 degrees C)

(2) The block technique of welding practised to minimize distortion

(3) The practice at some yards of removing the shaft for intermediate straightening and machining.

Down-time due to preheating was first reduced by lowering the preheat temperature to 40-50 degrees C, since stress measurements and heat-affected zone hardness tests did not appear to justify the existing level of 85 degrees C. A further reduction would result from the use of electric heating switched on in silent hours.

The block technique previously practised was next reviewed, and recently several shafts have been reinforced using full length weld runs, the longest being 21 ft. No undue distortion or other trouble was experienced, and the welding—in some cases three layers high—was completed without intermediate straightening or machining. With recent shafts this technique was coupled with a north-south sequence, with the initial run in any work period laid on the high side of the shaft. Final distortion was found to be comparable with that experienced in the N.S.E.W. technique.

The results of this and earlier work will be contained in new instructions soon to be issued in which the following procedure will be recommended.

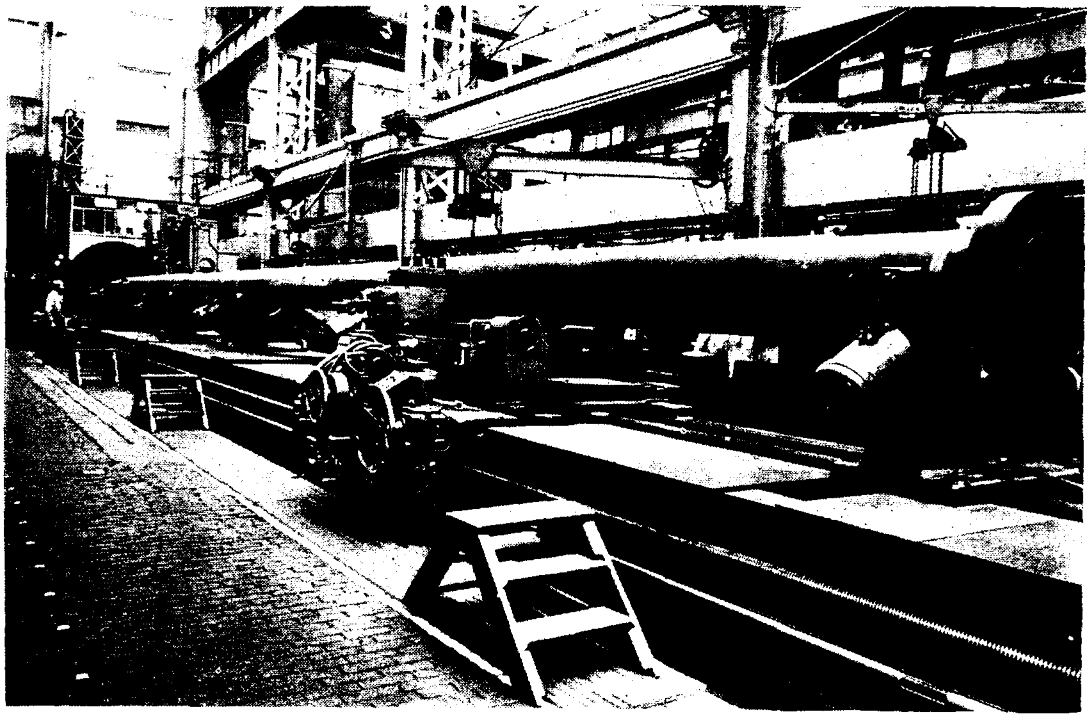

FIG. 8—ONE OF THE LARGER TAIL SHAFTS BEING SET UP IN THE LATHE FOR MACHINING

Preparation Prior to Automatic Welding

The shaft is cleaned and the journal surfaces are machined concentrically to remove pitting and grooving of the type shown in FIG. 7. FIG. 8 shows one of the larger shafts being set up in a lathe for machining. The machining run-off angles are specified to avoid producing sharp changes in section. At this stage a sample of the turnings is analysed for carbon and manganese. Any isolated deeper pits may be ground out and, subject to a satisfactory crack detection, refilled by metal arc welding, using a fairly large gauge low-hydrogen electrode and a local preheat of 150 degrees C. Any local build-up is to be ground or machined flush and the whole of the journal is to be magnetically crack detected. This inspection is necessary to ensure that any corrosion fatigue cracks are completely removed since, as shown in FIG. 9, welding over such cracks is a dangerous practice and may well leave them sealed beneath the surface of the weld metal, to propagate in service.

Automatic Welding

A $1\frac{1}{2}$-2 per cent manganese wire and a high-manganese flux are mandatory for submerged arc welding. The whole journal length is preheated to approximately 50 degrees C before the first weld is laid. Heat input is limited to 50 kJ/in. for all shafts with a wall thickness less than $2\frac{1}{2}$ in., although this may be increased to 65 kJ/in. for thicker-walled shafts. Standard conditions employed at Portsmouth are $\frac{1}{4}$ in. diameter wire, 600 amps. A.C. and a carriage speed of 12 inches per minute.

FIG. 9—CORROSION FATIGUE CRACK IN THE SHAFT JOURNAL 'SEALED' IN BY WELD REINFORCEMENT (APPROX. × 60)

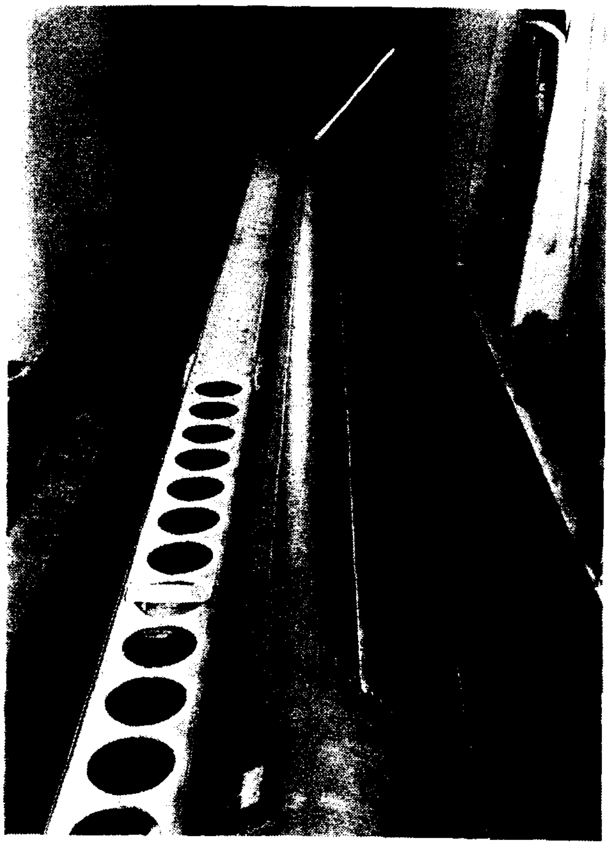

FIG. 10—WELDING PARTLY COMPLETED. WELDS ARE LAID IN A N—S SEQUENCE AS SHOWN

The welds are laid full length in a north-south sequence as shown in FIG. 10 until the reinforcement is complete. A short length of the shaft illustrated required an extra layer of deposit, and this was completed before the overall length of 21 ft was started. A scribing block is positioned at a fixed point just outside the welded portion and the bowing of the shaft checked after each run. Successive runs are laid in such a manner that the shaft tends to return to the neutral axis, and it is here that the experience of the operator really counts. Generally the first run of the day is laid on the convex side and the last on the concave. The appearance of the completely welded journal is shown in FIG. 11.

Straightening

When the shaft has cooled out, the eccentricity is checked and a straightening weld is laid on the convex side. This is repeated as necessary until the shaft is within $\frac{1}{8}$ in. of truth. The shaft is then transferred to the lathe, held concentric in steadies, and a rough machining cut is made over the welded length. The steadies are then released and the shaft clocked for eccentricity at 12-inch stations. Thermal straightening by oxy-acetylene flame is applied at the point of maximum convexity and repeated at adjacent points as necessary. The process is shown in FIG. 12. The location and number of heats which are necessary demand considerable experience on the part of the operator. When poor response to thermal straightening is encountered the welded portion of the shaft is heat treated as described earlier. Final thermal straightening to within fine machining limits is then straightforward.

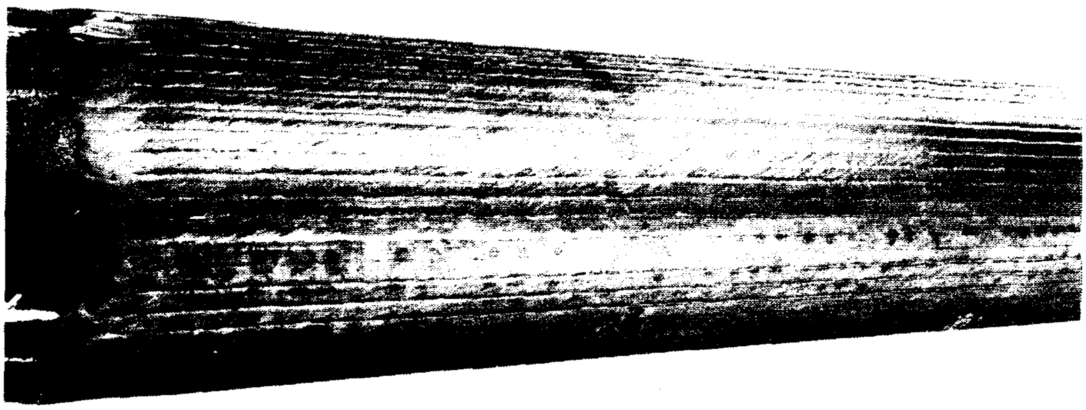

FIG. 11—WELDING COMPLETED. THE REINFORCEMENT IS TWO LAYERS HIGH

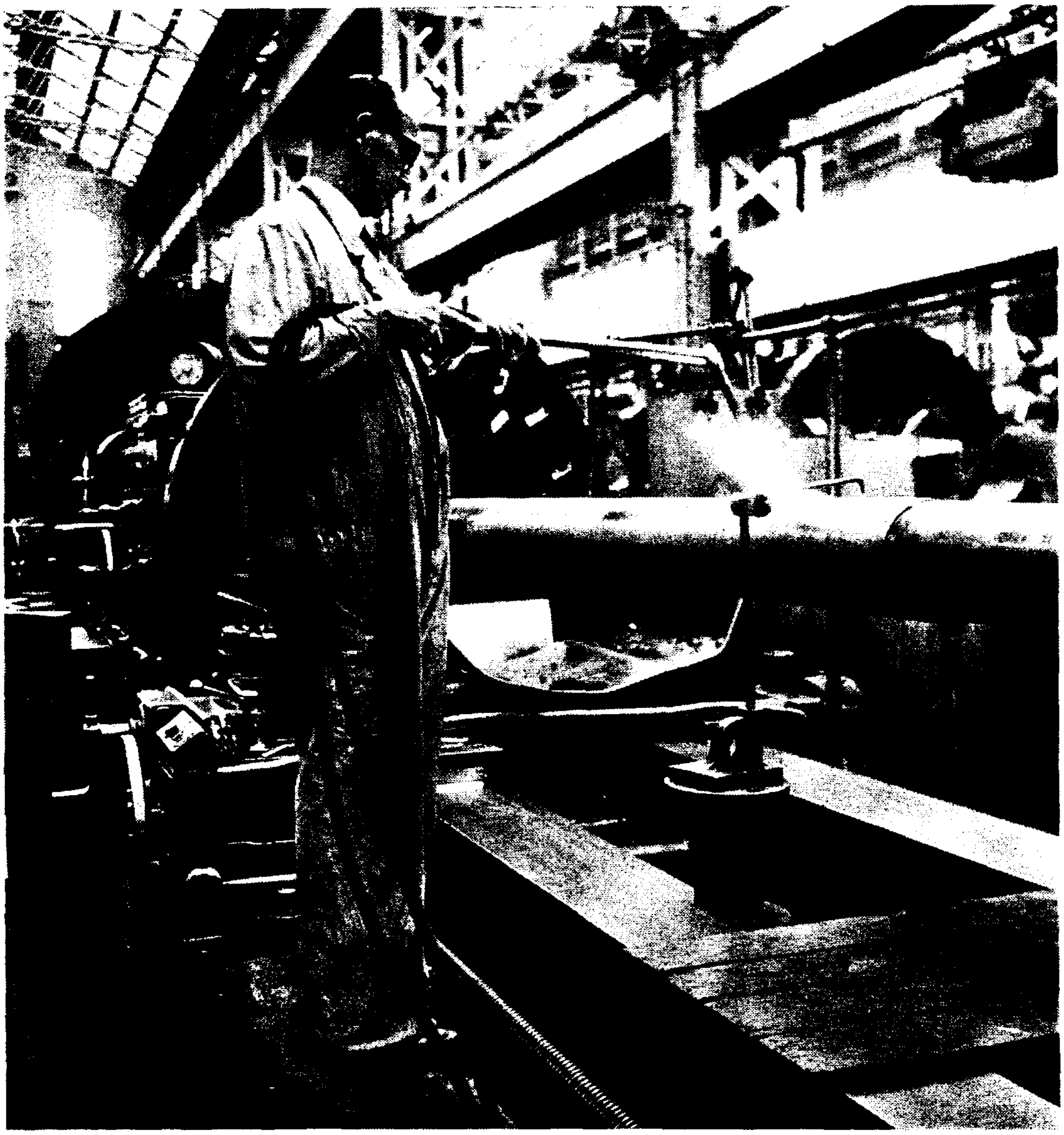

FIG. 12—THE APPLICATION OF THERMAL STRAIGHTENING

FIG. 13—THE JOURNAL MACHINED. WHEN THE EXPOSED LENGTH (LEFT) HAS BEEN PROTECTED WITH FIBRE-GLASS AND EPOXY RESIN, THE SHAFT WILL BE READY FOR SERVICE

Completing the Shaft

The journal is now fine machined to size as shown in FIG. 13 and the coupling refaced normal to the longitudinal axis. The exposed lengths of the shafts are then protected by wrapping with fibre-glass tape and impregnating with epoxy resin. The completed shaft is then ready for replacement in the ship.

Conclusions

Implementation of these latest techniques has considerably reduced the time required to reclaim a propeller shaft, and current commitments can now readily be met with existing equipment. There has also been a very substantial saving in the cost of reclamation.

A propeller shaft of the Battle Class destroyer H.M.S. *Agincourt* was recently reclaimed at Portsmouth at a total cost of less than £750; a figure which compares very favourably with an estimated replacement cost of £7,000.

Statistical evidence covering the hundreds of shafts reclaimed by welding gives overwhelming proof of the success of the process, since the known instances of failure are very few; of those examined, welding was invariably eliminated as a principal cause of failure.

Acknowledgments

The above work was carried out in the Central Dockyard Laboratory and Engineering Department of H.M. Dockyard, Portsmouth, but the opinions expressed are those of the author. The assistance of colleagues and members of the Engineering Department is gratefully acknowledged. Particular thanks are due to Dr. C. D. Lawrence and Mr. J. N. Bradley of the above laboratory and to Mr. R. S. C. Medhurst, Admiralty, Bath.

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