Lecture 7

WELDING 304L STAINLESS STEEL TUBING HAVING VARIABLE PENETRATION CHARACTERISTICS

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ABSTRACT

Following difficulties with heat-to-heat variation in weld penetration enountered during GTA welding of stainless steel tubing, a program was undertaken to identify the cause of the problem and to develop remedial techniques. The variation in weld penetration was attributed primarily to differences in sulphur and, to a lesser extent, oxygen content, in broad agreement with a published model for such effects based on surface tension. The incorporation of copper alloy heat sinks into the standard welding head was successful in overcoming the problem. Both argon - 1% oxygen shielding gas and multipass welding procedures have been demonstrated to be promising alternative solutions, but these techniques have not been fully developed. To prevent the recurrence of the problem in future construction, a limit of 100-200 ppm sulphur has been included in the material specification for tubing purchases.

KEYWORDS

Stainless steel; 304L; tubing; Gas Tungsten Arc; variable weld penetration; sulphur; oxygen; heat sinks; argon-oxygen mixtures; multipass.

INTRODUCTION

Type 304L stainless steel tubing is used extensively in instrumentation systems for the CANDU (Canadian Deuterium Uranium) nuclear electricity generating stations. The systems in a typical reactor unit require some 50,000 m of tubing in sizes ranging between 6 mm OD x 1.2 mm wall thickness to 25 mm x 2.4 mm. Installation of this tubing involves about 15,000 butt welds. The welds are produced at site using a portable orbital Gas Tungsten Arc (GTA) welding machine which fuses the tube ends, without the addition of filler, inside a protective chamber flooded with argon. The welding current, rotation speed, and gas flows conform to a preset cycle, which is standardized for each tube size, under the control of the welding power supply (Delaney, 1978). Table 1 lists a typical standard procedure and also gives details of some of the experimental techniques described below. Many of the instrumentation systems contain reactor primary coolant, and lack of fusion defects in the welds are not acceptable.

This method was used to join instrument tubing during the past construction of the 4-unit Bruce 'A' and Pickering 'A' generating stations in Ontario. Experience at that time was very satisfactory, with low weld defect rates. Recently, however, during the construction of several new generating stations, difficulties have been experienced with variable and irregular weld penetration causing lack of fusion defects in the welds. These effects, which occurred although the standard welding procedures were being used, were observed only when joining certain batches of tubing. The increased weld reject rates which resulted, and the need for increased inspection of welds and sorting of tube material according to weldability, delayed and added substantially to the costs of tubing installation.

Therefore, a research and development program was conducted with the objective of identifying the nature of the material-related variation in tube weld quality, and developing remedial techniques for field application. The results of this program are outlined in the following sections.

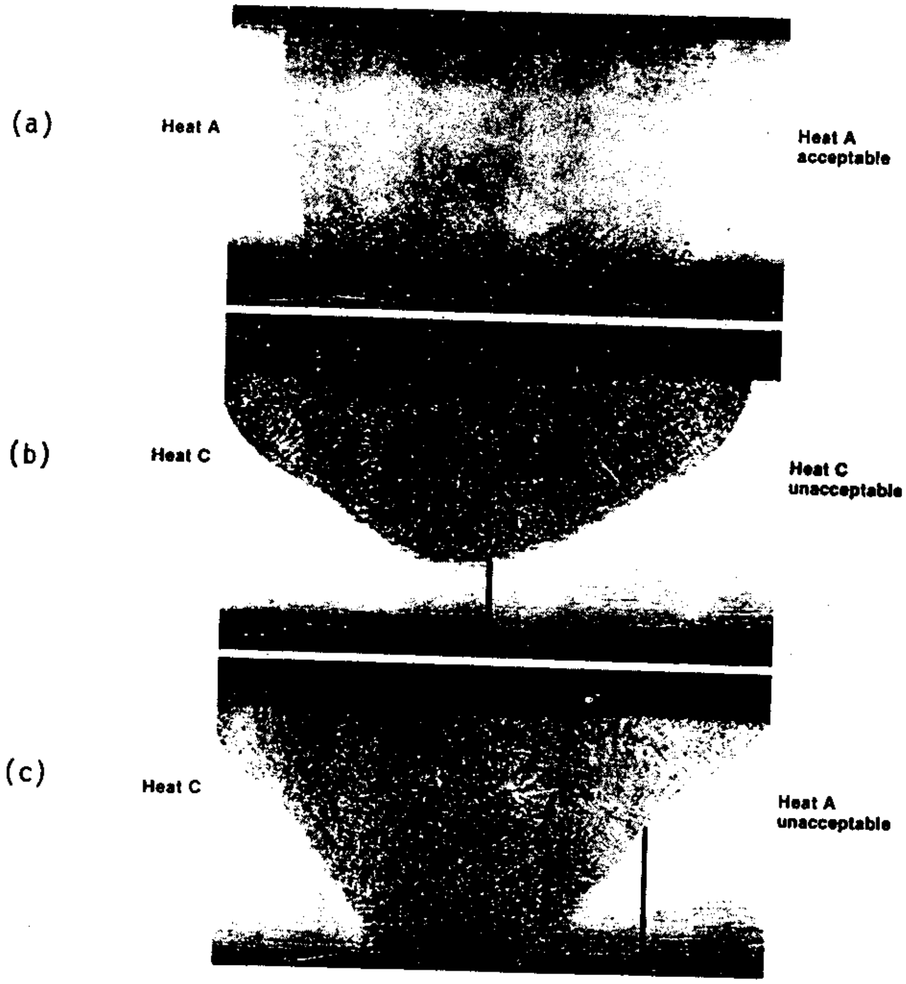


Fig. 1 Base material effects on GTA weld cross-section in 25 mm x 2.4 mm 304L tubing.

THE NATURE OF MATERIAL-RELATED VARIATION IN TUBE WELD QUALITY

Field experience had been that the differences in welding behaviour occurred between heats of tubing, and this was confirmed by subsequent investigation. Some heats of tubing would give wider, shallower welds than normally expected using the standard welding procedures, as illustrated in Figs. 1(a) and (b). Different heat treatment lots, or even different tube sizes, within a heat exhibited similar behaviour. Heats of tubing were thus classified broadly as having a high ratio of weld penetration depth/width (D/W) or a low D/W. The D/W ratio has been found to be a useful indicator of the fusion characteristics of a material, for instance (Metcalfe & Quigley, 1977).

Of further, major concern was the fact that when high D/W tubes were welded to low D/W tubes, the weld paradoxically melted more of the low D/W tube. This was termed 'weld puddle shift' and is illustrated in Fig. 1(c). The skewed weld cross-section again often caused lack of joint fusion. When weld puddle shift occurred, the weld pool assumed an asymmetric, kidney-shaped appearance in contrast with the normal oval shape, as illustrated in Fig. 2. In this case, the deepest weld penetration occurred off-centre in the pool, towards the rear on the low D/W tube side.

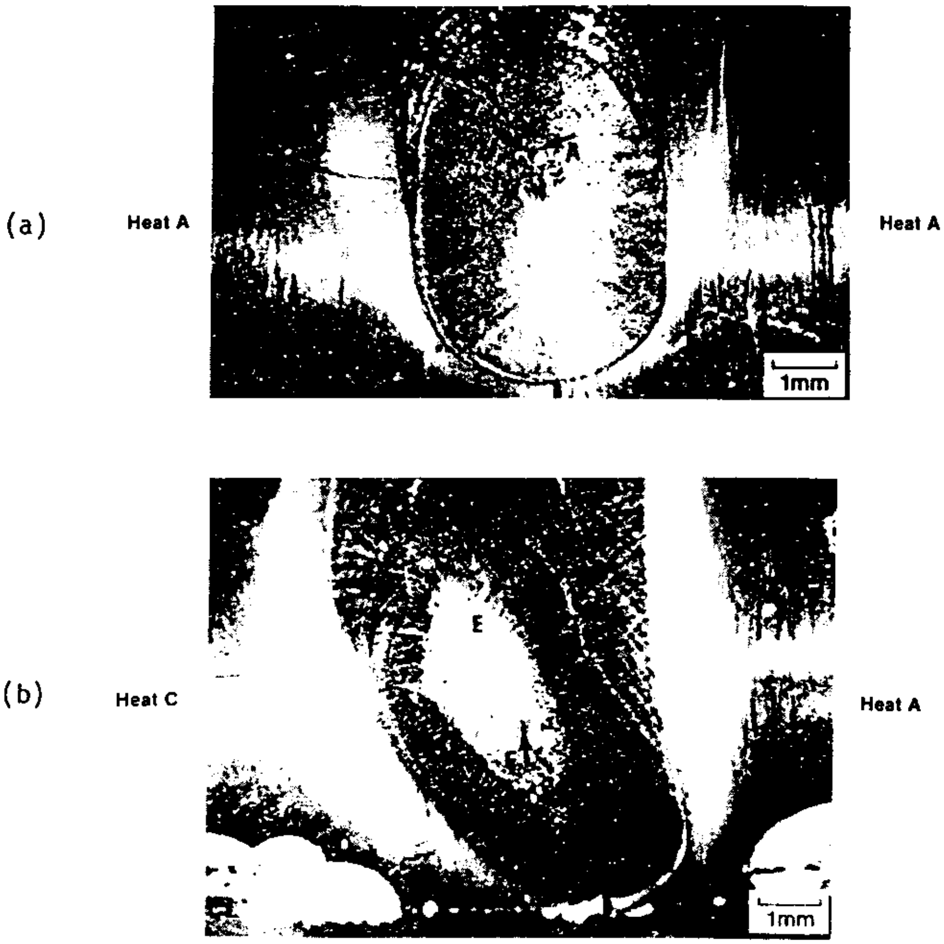


Fig. 2 Weld pool shape when joining a) similar materials, and b) dissimilar materials.

The tubing in the construction inventory was studied in order to identify factors which correlated with welding behaviour. A strong link between weld D/W or weld puddle shift and chemical composition, primarily the sulphur content, emerged from this study. Heats of tube with a low sulphur content, less than 40 parts-per-million (ppm), were those which gave reduced or irregular penetration when welded to themselves and which attracted the weld when joined to tubes having a high sulphur content, greater than 80 ppm. For instance, in Fig. 1, heat 'A' had a sulphur content of approximately 90 ppm and heat 'C' less than 30 ppm.

The link between the sulphur content and weld puddle shift was further explored as follows. Samples from 19 heats of 9.5 mm 304L tubing in the construction inventory, with sulphur contents in the range 15 to 140 ppm, were welded in turn to tubes at the high and low ends of this range. The welds were then sectioned axially and prepared metallographically to enable precise measurement of the weld cross-section with respect to specially-made witness marks on the tube outer surface. Fig. 3 provides a key to weld dimensions defined by this technique. The change in weld location, in terms of centre-line shift, with sulphur content is illustrated graphically for the two cases by Figs. 4(a) and (b).

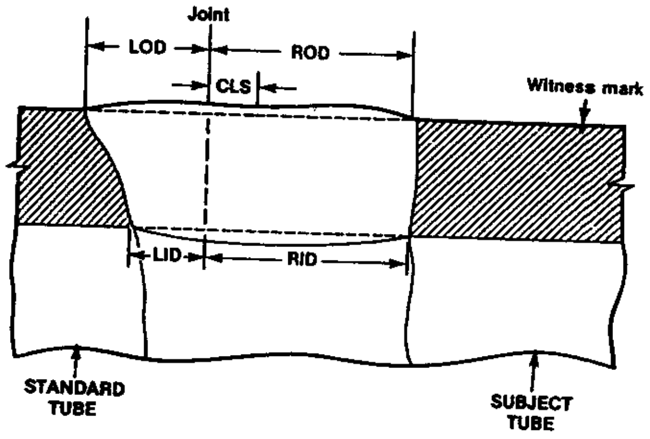
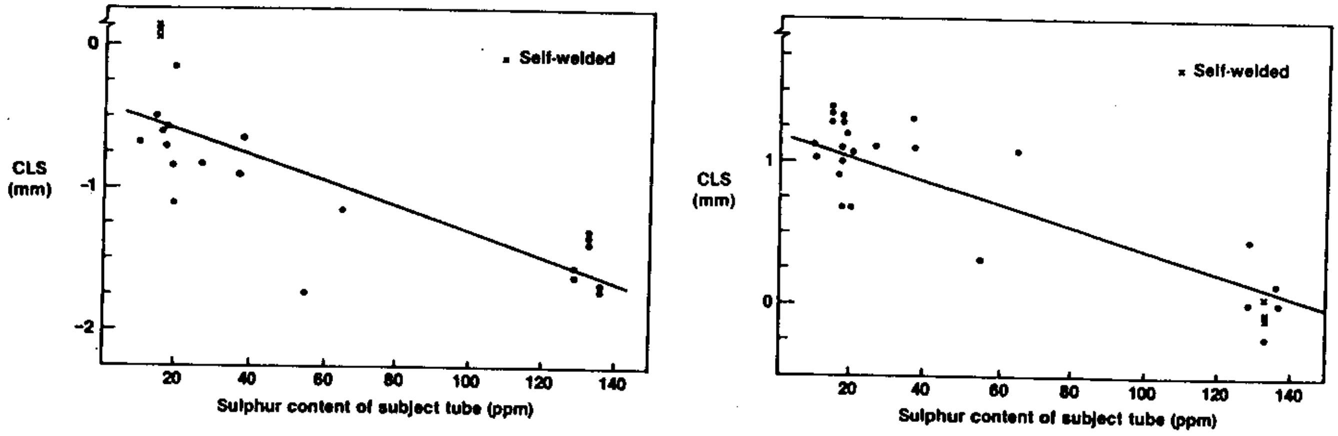


Fig. 3 Key to weld dimensions.



(a)

(b)

Fig. 4 Variation of CLS in 9.5 mm tubing when subject tubes are welded to: a) a 'low-sulpur' standard, S=15 ppm, and b) a 'high-sulphur' standard, S=133 ppm.

Other compositional factors could not be ruled out, however. Workers elsewhere have observed recently that variation in the oxygen content of austenitic stainless steels appears to cause changes in weld penetration (Fihey and Simoneau, 1982; Heiple and Roper, 1982a). A test for effects of oxygen was therefore carried out. Four heats were selected from the previous 19 which had sulphur contents of either 20 or 65 ppm and oxygen contents of approximately 40 or 80 ppm, forming a complete factorial experiment with sulphur and oxygen at two levels. These tubes were welded to a high-sulphur standard, then sectioned and measured as before. The results are illustrated in Fig. 5. Oxygen was observed to have effects similar to, but somewhat weaker than, sulphur.

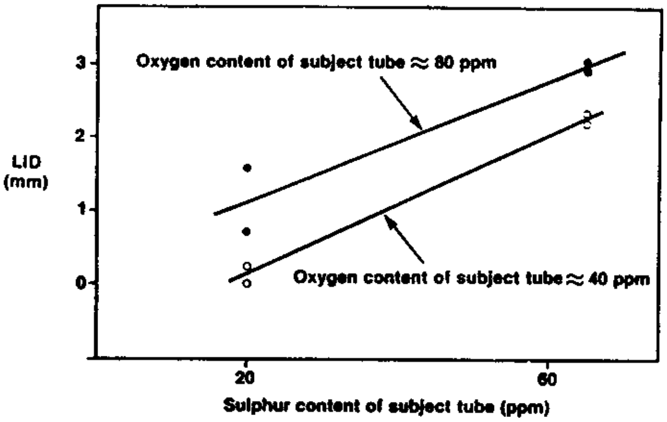


Fig. 5 Variation of LID with sulphur and oxygen content in 9.5 mm tubing.

It has been suggested also that the level of alkali or rare-earth elements in austenitic stainless steels can affect welding characteristics (Ludwig, 1968). According to the tube supplier, rare-earth treatments were not used at any time during steel refining and, consequently, the levels of these elements generally would be expected to be less than 10 ppm. There was no evidence of significant differences in the calcium content of heats having different penetration characteristics. However, there was some indication from the field trials that low sulphur heats having slightly increased levels of aluminum, titanium, or boron exhibited more extreme low D/W behaviour than other low sulphur heats. The results with low sulphur tubing generally were more variable and less well-explained on the basis of sulphur alone, as is seen clearly from the scatter in Figs. 4(a) and (b).

DEVELOPMENT OF REMEDIAL TECHNIQUES FOR FIELD APPLICATIONS

A welding problem which can be attributed to variations in material composition may be dealt with at that level. The material specification for the purchase of stainless steel tubing for instrumentation systems has been revised to limit sulphur content to the range 100-200 ppm, and to prohibit any new alloy or trace element additions. This should prevent a recurrence of the problem in future.

It was, however, necessary to deal with the existing tubing inventory. Interim guidelines for field welding were defined, prohibiting the joining of high sulphur (>80 ppm) tubing to low sulphur (<40 ppm) tubing. This approach did allow instrument tube welding to progress, but was slow and costly. Thus the development of more suitable long-term solutions remained a high priority. Of some seventeen techniques evaluated, the three described below provided sufficient promise in terms of effectiveness and ease of implementation in the field to merit further investigation and development.

Copper Alloy Heat Sinks

One control concept was to limit the extent of tube melting on either side of the weld joint by positioning heat sinks around the tubes being welded. Accordingly, prototype heat sinks were manufactured from a copper alloy in the form of relatively thick cylindrical sleeves machined to fit around 9.5 mm diameter tubing. This technique was found to be extremely successful, reducing weld puddle shift to negligible values even for the most difficult to weld tube combinations. Therefore, a welding procedure was developed (see Table 1) and copper alloy heat sinks fitted into the weld heads for use in field construction, as illustrated in Fig. 6. These modified weld heads have now been used in production for some time with weld quality and reject rate as good as, or better than, the levels attained prior to the emergence of the weld puddle shift problem.

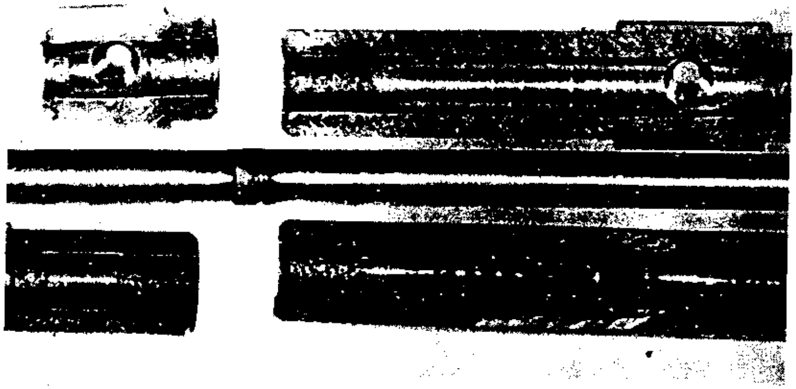


Fig. 6 Copper heat sinks for 9.5 mm tubing.

The heat sink design was complicated by several factors. The thick section heat sinks used in the preliminary trials could not be fitted into the low profile weld head for small diameter (≤12.6 mm) tubing, which is required to deal with areas of restricted access. Clearance within this head limited heat sink thickness to 1.8 mm. With thinner section heat sinks, problems were quickly encountered when bending of the longer heat sink (see Fig. 6) led to poor surface contact and loss of effectiveness. Even the use of a high-strength heat-treated beryllium copper alloy did not alleviate this problem, so relatively minor modifications were finally made to the existing weld heads to allow the incorporation of heat sinks

TABLE 1 - WELDING CONDITIONS FOR 9.5 mm TUBING

Technique	Start Current (A)	Finish Current (A)	Fixture Rotation Speed (RPM)	Arc Length (mm)	Shield & Backing Gas	Other
Std. Procedure	35	26	4.6	1	Argon	
Copper Heat Sinks	54	54	1.7	1	Argon	Heat sink gap = 5 mm
Argon - 1% Oxygen	38	25	4.0	1	Argon - 1% O_2	
Multipass	Pulsed Current 54 peak 33 background		8.5	1	Argon	7 passes (continuous)

4.6 mm thick. This increased cross-section provided the necessary heat absorption and mechanical stiffness characteristics.

An additional concern noted during the development program was the occurrence of occasional copper contamination of the weld surface. Although this was mostly innocuous mechanical transfer onto the solidified weld or tube surface, a few isolated instances of unacceptable fusion line defects were observed. A related issue was the fact that performance of the heat sinks in controlling weld puddle shift could be adversely affected by wear, which would reduce surface contact. Wear-resisting nickel plating and titanium carbide coatings were evaluated. The titanium carbide coating performed extremely well, and was consequently included in the heat sink design. Coated areas are characterized in Fig. 6 by their darker appearance.

Shielding Gas Mixtures and Multipass Procedures

Two other techniques for controlling weld puddle shift were sufficiently promising to merit more detailed study. Previous workers have reported that small additions of oxygen or hydrogen to the argon shielding gas improves weld penetration in difficult to weld stainless steel tubing (Carrick & Paton, 1982; Fihey & Simoneau, 1982). Three shielding gas mixtures were tested: argon - 0.1% oxygen, argon - 1.0% oxygen and argon - 5% hydrogen. To find appropriate welding procedures for the three gas mixtures, systematic experiments were employed following a response surface methodology (Wang & Ramussen, 1972), with welding start current, end current, and welding fixture travel speed being the factors varied.

The test results indicated that the argon - 1.0% oxygen mixture significantly reduces weld puddle shift using the welding procedure given in Table 1. Surprisingly, the argon - 0.1% oxygen and argon - 5% hydrogen mixtures were found to provide no significant benefit. Due to the success of the copper heat sink solution, however, no further effort was made to develop the argon - 1% oxygen technique for field use.

The concept of using a multipass welding technique for instrument tube welding stemmed from the observation that for the standard welding procedure, the small overlapping weld bead formed during current slope-down was typically much better centred than the main weld bead itself. In the preliminary test program, a seven pass pulsed current welding procedure was identified which provided promising results. This procedure, given in Table 1, was then used to make about 50 identical welds with each of three commercially available tube welding systems. Although weld puddle shift was substantially reduced on average, the phenomenon could not be controlled consistently and some cases of lack-of-fusion were observed. It is possible that the welding equipment may have been at fault in being unable to provide satisfactory repeatability of programmed welding parameters under relatively severe working conditions. Since no attempt had been made to optimize the multipass welding procedure prior to consistency testing, however, it is more likely that the procedure used may have been unnecessarily sensitive to relatively minor variations in the set welding parameters. Again, due to the success of the heat sink technique, no attempt was made to further develop the multipass procedure for field application.

DISCUSSION

Causes of Material-Related Variation in Tube Weld Quality

Base material effects on GTA weld penetration have been reported in journals and conference proceedings for the past 25 years. The problem illustrated here displays many of the symptoms described in the literature, namely: weld D/W varies between heats of material and, when different heats are joined, the weld is attracted or skewed towards the low D/W heat, as shown previously by Moisio & Leinonen (1980). It is this variability that is of practical significance and which leads to unacceptable results in some cases when standard welding procedures are applied.

The variability of weld penetration is generally believed to be due to differences in the residual or minor alloying content of the material, since it occurs mainly between heats of material or between materials made by alternative refining routes, such as air melted or vacuum arc refined steels. Previous studies have not, however, produced widespread agreement on which specific elements are the cause. On aggregate, the results have simply emphasized the lack of understanding of the basic mechanisms (Glickstein & Yeniscavich, 1977).

Heiple and co-workers (1980, 1981, 1982a) recently conducted a well-controlled series of experiments which showed that sulphur, oxygen, selenium, tellurium, cerium, and aluminum additions to austenitic stainless steels affect fused zone shape. Heiple & Roper (1982b) proposed a model to explain these results based on the premise that fluid flow is generally the major factor influencing weld pool shape. In particular, the model states that surface tension gradients across the surface of the weld pool cause fluid flow known as 'Marangoni Convection', and that the surface tension gradients are sensitive to small concentrations of surface active elements in the weld pool, as illustrated schematically in Fig. 7.

Our investigation indicates that the weld D/W characteristics of heats of 304L tubing, irregular weld penetration, and weld puddle shift are related to the chemical composition of the tubing. Material with relatively low sulphur content exhibits low D/W ratios whereas material with higher sulphur content exhibits higher D/W ratios. When joining high to low sulphur material, the weld shifts towards the low sulphur material. Varying oxygen content has effects similar to, but somewhat weaker than, those of sulphur and the effects of the two elements appear to be additive over the range tested. Sulphur and oxygen are surface active in liquid iron, therefore our results may be interpreted directly in terms of the model above (Figs. 1 and 7). Using the data for surface tension given by Gupt and others (1976) it is possible to show approximately, following the simple analysis of Andersson (1974), that the surface tension forces are of a sufficient order of magnitude to cause convective motion. The poorer correlation between sulphur and weld puddle shift with lower sulphur tubing may be due to other elements assuming greater importance as the level of the principal surface active component, sulphur, is reduced. Variation in oxygen content may well account for much of the scatter in Fig. 4. The possible effect of aluminum, titanium, and boron at low sulphur levels may be explained on the basis that, although they are not surface active, they would combine with oxygen, effectively removing the remaining surface active component from the system.

Alternative explanations for minor element effects on GTA fused zone shape will be found in the literature. Many of these invoke interaction between the base material and the welding arc, for instance as proposed recently by Fihey and Simoneau (1982) and by others previously (Bennet & Mills, 1974; Ludwig, 1968; Metcalfe & Quigley, 1977; Savage & co-workers, 1977). The useful heat from the GTA arc is produced mainly in the current carrying region on the work-piece surface known as the 'anode spot' due to the work function of the surface and the anode voltage drop (Nestor, 1962; Quigley & co-workers, 1973; Schoek, 1963). According to explanations of this type, the physical nature of the arc is sensitive to small concentrations of certain elements in the workpiece, thereby affecting the heat generation in, or the location of, the anode spot. It is well known also that fluid motion in the weld pool may be caused by electro-magnetic induction, which can affect weld pool shape appreciably, depending on the electrode geometry and the current distribution on the surface (Andrews & Craine, 1978; Lawson & Kerr, 1976; Woods & Milner, 1971).

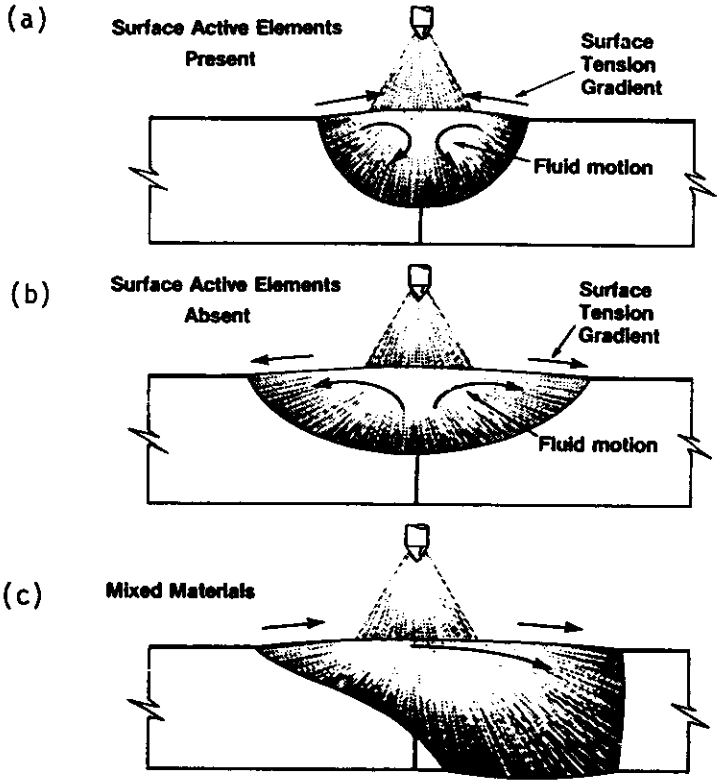


Fig. 7 Marangoni Convection model for minor element effect on GTA fused zone shape. (After Heiple and Roper 1982b).

However, Heiple and co-workers(1983) recently reported an experiment in which a defocussed laser was used to produce weld beads similar to GTA welds. Surface active elements were found to have effects on the laser weld D/W similar to those reported earlier for arc welds, in the absence of any possible arc/material interactions or electromagnetically-induced fluid flow. In view of this most recent work by Heiple and colleagues, we feel that our results with production heats of steel are best explained in terms of the surface tension model and, conversely, that our results lend support to this model as indicating the primary cause of base material induced variation in GTA fused zone shape.

Despite the broad agreement between our results and the model predictions, there remain several detail points which require elucidation, concerning especially the case of weld puddle shift when different heats are joined. From the shapes assumed by the weld pool, Fig. 2, the patterns of fluid flow must be more complex than that depicted in the simple model of Fig. 7(c). Further, it is unclear how compositional differences across the surface of the weld pool could persist , strongly in view of the vigorous motion which they are supposed to cause, and therefore how weld puddle shift could be other than a transient phenomenon at the beginning of a weld bead. In connection with joint tracking sensors, Chin and colleagues (1983) showed using infra-red thermography that a slight offset of the arc heat source from the interface between two plates causes a marked perturbation in the classical symmetric pattern of isotherms around the moving weld pool. Preferential heat transfer to one side of the joint by convection in the weld pool may be viewed in effect as an offset of the heat source from the joint, and the thermal resistance of the interface would have similar effects on the temperature field around the weld pool. It may be that surface tension driven motion continues weakly throughout the weld due to the melting of fresh material at the front of the pool, serving to initiate weld puddle shift, which is then exacerbated by the effect of the interface on the thermal field. It would be interesting to verify this proposal experimentally by changing the thermal resistance of the interface, perhaps by diffusion bonding prior to fusion welding.

Practical Solutions

The heat sinks are effective because they permit a higher heat input to the weld pool, overwhelming imbalances in heat transfer due to convective motion. The sensitivity to surface contact conditions demonstrates that the mechanism is a thermal effect rather than a direct influence on the arc. The heat sinks involved only minor changes to the welding procedure and welding equipment, and have been successfully applied in the field to a variety of tube sizes. As an indirect benefit, the welding procedure now has greater tolerance to small changes in welding parameters.

The results with gas mixtures were somewhat contrary to those reported previously. Fihey and Simoneau found that 1% oxygen tended to reduce penetration whereas 0.1% oxygen improved it. This discrepancy is possibly due to differences in welding techniques, since we found the effectiveness of the 1% oxygen mixture to depend on the welding parameters. Argon - oxygen mixtures would be very easy to apply in practice, using premixed bottles. The results are also of academic interest because the increased penetration may be explicable in terms of the Heiple and Roper model. Clearly this is a candidate for further research.

The results with the continuous multipass welding procedure also indicated some, inconsistent, improvement. It is uncertain whether the mechanism in this case is homogenisation of the weld metal by successive passes or equilibration of the thermal field around the weld between subsequent passes. With modern equipment, multipass orbital welding is easily achieved, so that this technique also would be worth further investigation.

A longer term solution is to specify the content of surface active elements in order to ensure uniform weld penetration characteristics. We believe that this may be readily achieved by restricting the sulphur content to between 100 and 200 ppm. Tubing has been ordered to such a specification and the preliminary indications are of satisfactory weldability. The major problem with this route is controlling the unreported residual elements. The Heiple and Roper model predicts that if sulphur is 'high' then the effects of varying concentrations of oxygen or oxygen getters such as aluminum would be minimal. However, elements which combine with sulphur, such as cerium, might be expected to induce low D/W behaviour even if sulphur is high. All such elements and their effects have not been identified.

CONCLUSIONS

Heat-to-heat variation in the welding characteristics of 304L tubing has been attributed to differences in the level of minor elements, primarily sulphur. Tubing with sulphur contents less than 40 ppm exhibits reduced or irregular penetration compared to tubing with higher sulphur contents and, when low sulphur tubing is joined to higher sulphur tubing, the weld shifts markedly towards the low sulphur side. The oxygen content appears to have additive effects similar to, but somewhat weaker than, those of sulphur, and there is some evidence that also the levels of aluminum, titanium, and boron affect fused zone shape when sulphur is low.

The results are in broad agreement with a published hypothesis for minor element effects on fused zone shape based on surface tension induced motion in the weld pool.

Copper heat sinks are a practical and effective means of controlling weld puddle shift and irregular penetration in tube welding. Argon-oxygen shielding gas mixtures and multipass welding may be potential alternative remedies, but require further work to demonstrate consistent improvements. Specifying a minimum limit as well as a maximum for sulphur content of 100 ppm and 200 ppm respectively will result in more uniform weldability of future material supplies.

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REFERENCES

Andersson, D. (1974). Streaming due to a thermal surface tension gradient. Weld. Res. Abroad, 20, 55-64.

Andrews, J.R. and R. Craine (1978). Fluid flow in a hemisphere induced by a distributed flow of current. J. Fluid Mech., 84, 281-289.

Bennet, W.S. and G.S. Mills (1974). GTA weldability studies on high-manganese stainless steel. Weld. J., 53, 548s-553s.

Carrick, L. and A. Paton (1982). Materials and welding of small bore pipework for nuclear fuel reprocessing plant. Proc. Conf. Welding Technology for Energy Applications, American Society for Metals, Metals Park, Ohio. 281-289.

Chin, B.A., N.H. Madsen, and J.S. Goodling (1983). Infrared thermography for sensing the weld process. Oral presentation to the 64th American Welding Society Annual Convention, Philadelphia, Pennsylvania.

Delaney, M. (1978). Metal Constr., 10, 32-33.

Fihey, J.L. and R. Simoneau (1982). Weld Penetration Variation in GTA welding of some 304L stainless steels. Proc. Conf. Welding Technology for Energy Applications, American Society for Metals, Metals Park, Ohio.

Glickstein, S.S. and W. Yeniscavich (1977). A review of minor element effects on the welding arc and weld penetration. Bulletin No. 226, The Welding Research Council, New York.

Gupt, K.M., V.I. Yavoiski, A.F. Vishkarov, and S.A. Bliznukov (1976). Study of the effect of concentration and temperature on the surface tension of the Fe-O-S system. Trans. Indian Inst. of Metals, 29, 286-291.

Heiple, C.R., R.J. Cluley, and R.D. Dixon (1980). The effect of aluminum on GTA weld geometry in austenitic stainless steel. Proc. Conf. Physical Metallurgy of Metal Joining. The Metallurgical Society of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Warrendale, Pennsylvania. 160-165.

Heiple, C.R., and J.R. Roper (1982a). Effects of minor elements on GTAW fusion zone shape. Proc. Conf. Trends in Welding Research in the United States, The American Society for Metals, Metals Park, Ohio. 489-520.

Heiple, C.R. and J.R. Roper (1982b). Mechanism for minor element effect on GTA fusion zone geometry. Weld. J., 61, 97s-102s.

Heiple, C.R., J.R. Roper, R.T. Stagner, and R.J. Aden (1983). Surface active element effects on the shape of GTA, laser, and electron beam welds. Weld. J., 62, 72s-77s.

Lawson, W.H.S., and H.W. Kerr (1976). Fluid motion in GTA weld pools: Part 1, Weld. Res. Intl. 6, No. 5, 63-77; Part 2, No. 6, 1-17.

Ludwig, H.C. (1968). Current density and anode spot size in Gas Tungsten Arc. Weld. J., 47, 234s-240s.

Metcalfe, J.C. and M.B.C. Quigley (1977). Arc and pool instability in GTA welding. *Weld. J.*, *56*, 133s-139s.

Moisio, T. and J. Leinonen (1980). The influence of minor elements on the welding arc and weld penetration in austenitic stainless steel. *Proc. Conf. Arc Physics and Weld Pool Behaviour*, The Welding Institute, Abington, Cambridge, 285-288.

Nestor, O.H. (1962). Heat intensity and current density distributions at the anode of high current inert gas arcs. *J. Appl. Phys.*, *33*, 1638-1648.

Quigley, M.B.C., P.H. Richards, D.T. Swift-Hook, and A.E.F. Gick (1973). Heat flow to the workpiece from a TIG welding arc. *J. Phys. D.: J. Appl. Phys.*, *6*, 2250-2258.

Savage, W.F., E.F. Nippes, and G.M. Goodwin (1977). Effect of minor elements on fused zone dimensions of Inconel 600. *Weld. J.*, *56*, 126s-132s.

Schoek, P.A. (1963). An investigation of the anode energy balance of high intensity arcs in argon. In W. Ibele (Ed.), *Modern Developments in Heat Transfer*, Academic Press, New York. 353-400.

Wang, K.K., and G. Ramussen (1972). Optimisation of inertia welding process by response surface methodology. *J. Eng. for Industry*, *94*, 999-1006.

Woods, R.A. and D.R. Milner (1971). Motion in the weld pool in arc welding. *Weld. J.*, *50*, 162s-173s.