IMPROVED MICROSTRUCTURE AND IMPACT TOUGHNESS OF LASER WELDS IN A PRESSURE VESSEL STEEL

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Abstract

This paper reports preliminary results from what is believed to be the first successful use of a rutile flux-cored filler wire in the laser welding of a pressure vessel steel (0.16C) to create a high level of acicular ferrite in the weld microstructure and extend high impact toughness to low temperatures (27J temperature at below -100°C).

Introduction

The capabilities and potential of laser welding are now well recognised where, for example, the single-pass penetration of a 10kW CO_2 laser can exceed 15mm. Consequently, there is considerable interest in the impact toughness of thick section laser welds in carbon-manganese and microalloyed steels, representative of those used in the constructional, pressure vessel and pipeline industries [1][2][3]. A feature of autogeneous welds in these steels is that the impact toughness can be modest, although tending to increase for higher welding speeds. However, the resulting higher cooling rates give a concomitant and very unwelcome increase in hardness. It is believed that the properties result from the generation of mixed microstructures consisting of ferrite with aligned MAC[4] and low-carbon martensite. The former has poor toughness whilst the latter contributes improved toughness but higher hardness. Acicular ferrite, known for its high resistance to cleavage fracture, is observed only rarely in the autogeneous welds.

It is acknowledged that there are two possible approaches to the problem which could avoid the need for post weld heat treatment. One route, carrying a heavy commercial penalty, is to continue with autogeneous welding but select carefully the composition of the parent plate, for example by specifying a low-carbon material. The other route is to use filler as a means of changing the composition and promoting acicular ferrite formation; filler additionally enables the process to cope with poor fit-up[5]. Much of the published work on the use of filler has concentrated on the use of solid metal wires, and some success is reported[6][7] in achieving improvements to microstructure and hence impact toughness whilst avoiding excessive hardness. Generally control of acicular ferrite formation does not appear to be achieved readily, although a study[7] of the laser welding of 0.17%C BS4360 Grade 50D plate in 8mm thickness showed that by widening the joint gap to 2mm i.e. maximising the amount of filler, up to 70% acicular ferrite could be obtained in the resulting low carbon equivalent weld metal and a 27J equivalent transition temperature of approximately -40°C could be achieved. However, at the present state of process development, thick section welding with a gap as wide as 2mm can require considerable care[6].

The factors controlling the formation of acicular ferrite are complex but intragranular nucleation on inclusions or second phase particles is believed to play a key role as described in a recent review by Hart[8] and references therein. There is a wide range of possible nucleants, and for example TiO is known to be a suitable candidate[9]. It was decided in the present work to investigate addition of TiO_2 to promote acicular ferrite in laser-welds. Initial attempts in which the joint faces were pre-painted with a slurry of TiO_2 and alcohol resulted in severely disrupted welds, but the use of a slurry with finely ground rutile flux showed more encouragement. Accordingly it was decided to carry out weld trials with a proprietary rutile flux-cored welding wire. Reported here are results for the latter together with, for comparison, results for a double-deoxidised solid welding wire and for autogeneous welding.

The use of a similar flux-cored wire in laser welding of C-Mn steel had been previously described[10]. However, there was no stated intention in that work to nucleate acicular ferrite. Indeed, acicular ferrite was apparently not seen (possibly due to the quite different welding parameters and joint configuration) and although good low temperature impact toughness was obtained, it was in very low (0.05%) carbon plate.

Equipment and Procedure

The welding was carried out with the Culham Laboratory 10kW CO_2 laser CL10 in the manner described for the earlier phases of the work[6]. Sample plates, each 500mm x 200mm x 13mm were clamped in pairs and traversed horizontally under the downward-going beam, the welding zone being protected by helium shrouding. For the filler welds, a commercial wire feed unit delivered the wire at approximately 45° to the plate surface and in the same direction as the workpiece movement.

The plate used was a fully-killed aluminium treated C-Mn steel to BS1501-224-490B. A product analysis is given in Table 1. The specification minimum yield strength was 365 Nmm^{-2} and the minimum tensile strength was 509 Nmm^{-2}. The material was received in the normalized condition, hardness 170 HV5, and the microstructure was banded ferrite/pearlite with a grain size of approximately 10μm. A Charpy impact transition curve was obtained for the steel and the 27J and 40J temperatures were approximately -60°C and -50°C respectively.

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The 1.6mm diameter MIG welding wire was a standard double-deoxidised composition corresponding to BS 2901: Part 1: A18 and an analysis of the wire is given in Table 1. The 1.6mm diameter flux-cored wire consisted of rutile (TiO_2) within a low carbon steel tube conforming to the specification AWS A5-20 (Table 1).

Immediately prior to welding, the machined edges were cleaned with propan-2-ol. The plates were close-butted for the autogeneous weld; for the filler welds, joint gaps of 0.75mm were made by placing shims at the ends of the plates. The autogeneous weld and the A18 filler welds were made with 9kW at the work whilst the flux-cored filler weld was carried out with 9.2kW at the work. A welding speed of 7mms-1 was used throughout.

The welds were subsequently assessed by visual inspection, metallography, weld metal chemical analysis (including O and N for the flux-cored filler weld only), hardness measurements and Charpy impact tests. The Charpy V-notch specimens were prepared according to BS 131: Part 2: 1972 with the notch located at the weld centre line, normal to the plate thickness and in the plane of the weld. Testing was carried out over a range of temperatures to establish a transition curve.

Experimental Results

Figure 1 shows the Charpy impact transition curves for the three welding conditions. As is usual in welds of this type, deviation of the fracture out of the weld metal occurred in some cases and these results are shown as open symbols in the figure. Some porosity was seen on the fracture surface of the A18 filler weld. It is not thought to have strongly affected the impact values since the transition curve was consistent with others[6] obtained for earlier welds without porosity. Table 2 summarises the 27J and 40J temperatures from Figure 1 together with corresponding weld metal hardness. Of particular note is a 27J temperature of less than -100°C for the flux cored filler weld.

Figure 2 shows representative microstructures of the three welds. The autogeneous weld exhibited considerable grain boundary ferrite outlining prior austenite grains. Large areas of ferrite with aligned M-A-C were present and there was also some blocky ferrite together with a small amount of low carbon martensite and ferrite - carbide interphases. The mean hardness was 269HV5. The A18 weld exhibited similar microstructural

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constituents together with a little acicular ferrite and the mean hardness was 294 HV5. In contrast to the preceding two, the microstructure of the flux-cored filler weld showed only small amounts of grain boundary ferrite, blocky ferrite and ferrite with aligned MAC, but large areas (estimated 60%) of fine acicular ferrite. The mean hardness was 275 HV5.

Table 1 shows also the results of chemical analyses of the weld metals. For the autogeneous weld it is seen that, in relation to the parent plate, a loss has occurred for most elements, presumably as a result of reactions and evaporation. For this reason it is likely that the oxygen content of the autogeneous weld was lower than the parent plate value of 120ppm. For the filler welds, this effect is masked by the alloying of the wire and plate compositions. Thus for example, the carbon level is depressed by the low level of C in the wires whilst the converse is true for silicon. However, it should be noted that the carbon level in these welds is still relatively high (0.13%). Perhaps unsurprisingly, the levels of oxygen and titanium in the flux-cored filler weld are high, 350 ppm for the former and 0.02% for the latter (cf <0.01% Ti in the parent plate).

Discussion

This work has provided a convincing initial demonstration of the use of flux-cored wire to create, in a 0.16C plate, a laser weld microstructure having a high level of fine acicular ferrite, and to extend weld impact toughness to low temperature (27J at below -100°C). In particular, the microstructure and impact toughness are clearly superior to those obtained.in the corresponding autogeneous and A18 welds, where these were very similar to each other. In fact, the flux-cored wire produced much better results than even the best low-temperature impact performance seen in the earlier phase of this work. Those results were obtained with a Mo-bearing solid wire; the 27J temperature corresponded to -50°C and was obtained at a welding speed of 10mms^{-1} but the weld hardness observed (360 HV5) was significantly higher than for the flux-cored wire (275 HV5). Furthermore it should be stressed that the present gap size of 0.75mm is much more readily filled than the wider gaps which could otherwise be needed to achieve dilute carbon levels. The presence of the rutile flux does not appear to cause disruption even for the high energy density beam.

The analysis of the flux cored filler weld shows that titanium and oxygen have been introduced into the weld, and this is consistent with the observation of acicular ferrite which is known to nucleate on oxides of titanium. On the appropriate CCT diagram, the role of nucleants is to move the acicular ferrite phase field to shorter times so that it is intercepted by the rapid cooling curve which is characteristic of electron and laser beam welding. The cooling curve would otherwise result in creation of microstructures of the ferrite with aligned MAC type. The dependence of acicular ferrite formation on nucleant content has been characterised via weld oxygen level for a number of welding processes: in laser welding with A18 wire[7], acicular ferrite content was found to rise strongly with oxygen contents up to 75ppm, the highest level investigated; in electron beam welding[11] acicular ferrite was observed for oxygen levels above 130ppm and it was suggested that Ti-containing oxides were strong nucleating agents for acicular ferrite; submerged arc welding studies[9] showed that TiO nucleated acicular ferrite for oxygen levels in the range 100-150ppm. The oxygen level of the present flux-cored filler weld was 350ppm.

It is believed that the present results, although preliminary, represent a significant step towards achieving improved high energy density beam weld properties and thereby to enhancing exploitation of the technology. Clearly much further study is required to investigate, understand and optimise aspects such as the choice of additives and the process conditions (including heat cycle) which will control the composition, size and distribution of nucleants and thereby the creation of preferred microstructures for welds in particular steels.

References

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Table 1 Plate, Wire and Weld Metal Composition (wt%)

Material	C%	Mn%	Si%	P%	S%	Mo%	Ni%	Cr%	Al%	Cu%	Ti%	O ppm	N ppm
+Plate BS1501-224-490B	0.16	1.45	0.23	0.21	0.013	0.007	0.03	0.026	0.035	0.04	<0.01	120	60
+Wire BS2901.Part 1 A18	0.08	1.37	0.81	0.015	0.023	0.03	0.04	0.05	<0.01	0.32	<0.01	100	80
*Wire AWS A5-20		1.75	0.90	0.03	0.03	0.3	0.50	0.2	1.8				
+Weld Metal Autogeneous	0.13	1.33	0.17	0.019	0.012	<0.03	0.02	0.02	0.03	0.03	<0.01		
+Weld Metal A18	0.12	1.33	0.28	0.019	0.014	<0.03	0.02	0.02	0.03	0.09	<0.01		
+Weld Metal AWS A5-20	0.13	1.35	0.37	0.016	0.011	<0.03	0.02	0.03	0.02	0.03	0.02	350	60

+   Analysis
*   Rutile-cored wire; numbers refer to AWS specification chemical composition requirements - see footnotes therein.

Table 2   40J and 27J temperatures and weld metal
           centreline hardness (HV5)

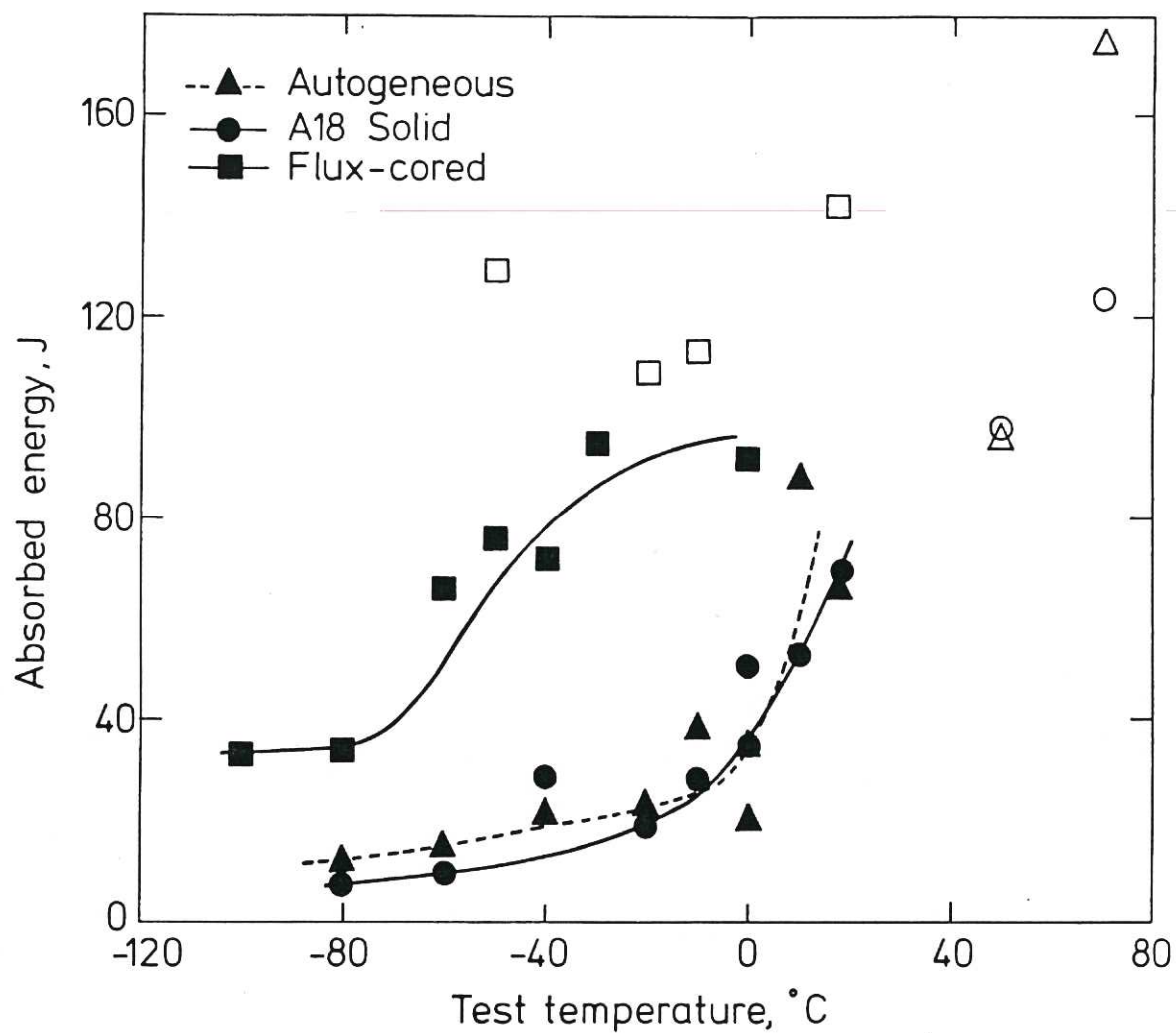| Wire Filler	27J	40J	Hardness Range $(\frac{min-max}{mean})$ HV5
Autogeneous	-10°C	0°C	$\frac{262-277}{269}$
A18	-10°C	0°C	$\frac{283-321}{294}$
AWS A5-20	<-100°C	-70°C	$\frac{262-293}{275}$

Figure 1.   Charpy impact transition curves for one autogeneous and two
filler welds.   Open symbols indicate that the fracture deviated
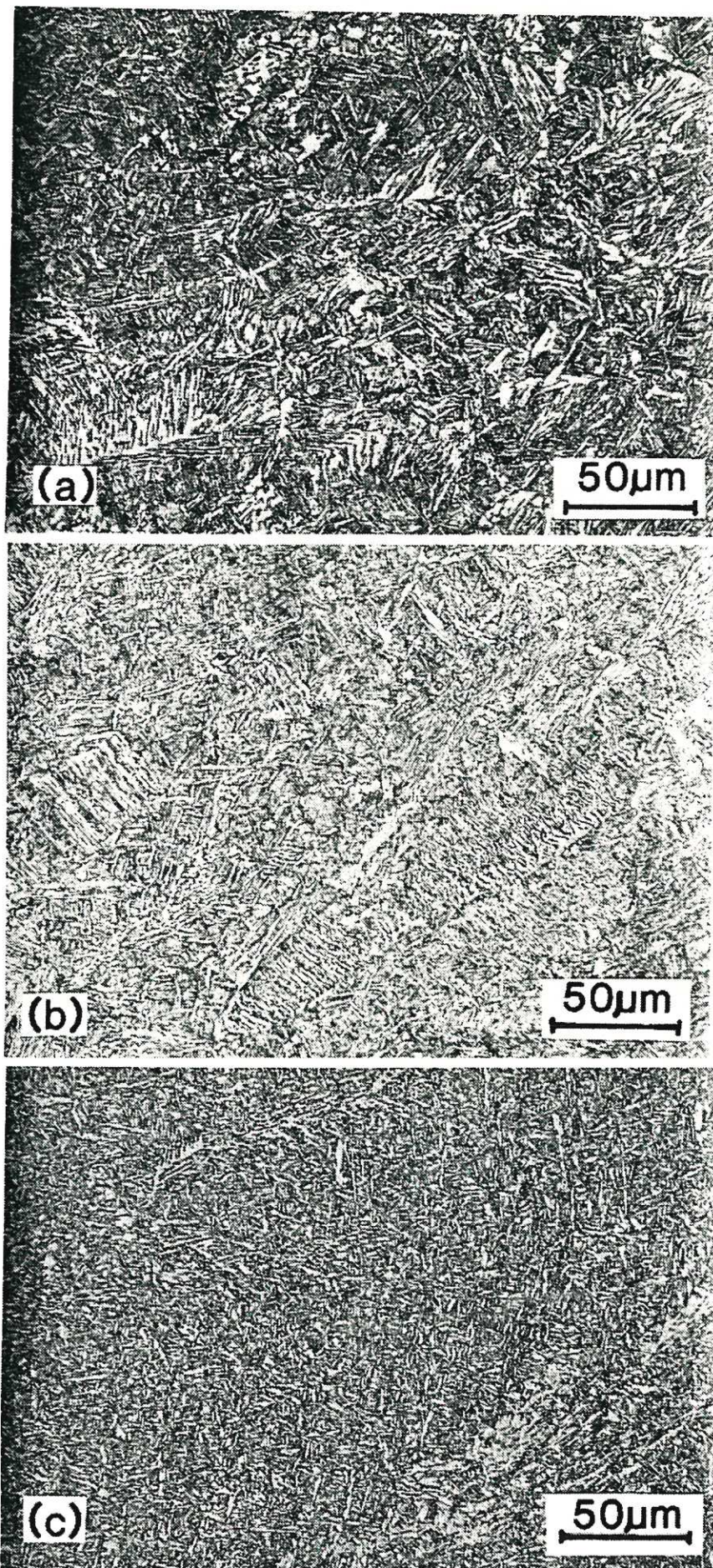out of the weld.

Figure 2.   Welds: (a) autogeneous; (b) with A18 filler; (c) with flux-cored
            wire.