Size distribution of oxides and toughness of steel weld metals

S. Terashima* and H. K. D. H. Bhadeshia

Experiments have been conducted to modify the size distribution of oxide particles in steel weld metals which have predominantly martensitic microstructures. It is found that the toughness improves significantly when the particles are refined, even when the total concentration of oxygen is unchanged in the process.

Keywords: Charpy impact toughness, Weld metal, Oxygen, Oxide, Microstructure, Size distribution

Introduction

The trend in strong weld metals is towards microstructures dominated by low carbon martensite. The role of oxide particles introduced into the metal during welding then becomes uncertain. The particles do not seem to affect the nucleation or growth of martensite. This is probably because this phase forms at relatively large driving forces and therefore does not rely on heterogeneous nucleation on oxides, and the oxides are not sufficiently finely dispersed to cause drag on the transformation interfaces. What is clear is that the non-metallic particles can initiate brittle cracks,[1–3] or voids[4,5] during ductile failure, both events leading to a deterioration in mechanical properties. Ideally, oxides should be eliminated from the microstructure of martensitic weld metals.[4,6] This of course is impractical, therefore, one alternative is to minimise the particle size so as to delay oxide related damage to the later stages of stress and strain. The purpose of the work presented here was to verify this alternative approach, even though it seems intuitively obvious that refined oxides should lead to better toughness when they do not influence the development of weld microstructure.

Experimental

Two 20 mm thick steel plates with ultimate tensile strength (UTS) of 780 MPa were welded using 1·2 mm diameter wires, in the flat position using the metal active gas (MAG) shielded arc welding technique (compositions in Table 1). A single pass was used to fill the 90° V butt using a nominal heat input of 3·4 kJ mm^{-1} and a welding speed of 3·3 mm s^{-1}. MAG was chosen to achieve various oxygen concentrations ranging between 20 and 600 ppmw (parts per million by weight) by controlling the composition of the shielding gas such as pure argon, 0·99Ar–0·01CO_2, 0·98Ar–0·02CO_2, 0·9Ar–0·1CO_2, 0·8Ar–0·2CO_2 and CO_2. The procedure has been described elsewhere:[6] the concentrations achieved are listed in Table 2. All chemical compositions reported here were determined using inductively coupled plasma spectrometry except for oxygen which was measured using combustion analysis. Tensile samples of 6 mm diameter were machined from the weld metal parallel to the welding direction. The measured UTS of the as welded sample produced under the shielding gas of 0·9Ar–0·1CO_2 was 778 MPa.

To alter the oxide size distribution, the as welded sample containing 350 ppmw O was remelted using the tungsten inert gas (TIG) shielded arc welding technique in a single pass (2·9 kJ mm^{-1}, 1·0 mm s^{-1}). To ensure the same cooling rate during both MAG and TIG welding, the samples were preheated in the latter case for 3·6 ks at 473 K, consistent with an equation owing to Kasuya and Yurioka,[7] which resulted in a reduction in the oxygen to ~90 ppmw (Table 3).

The microstructure was characterised qualitatively and quantitatively as described elsewhere,[6] and Vickers hardness and microhardness were measured on metallographic samples using a 98 and 0·49 N load respectively. The particle size distributions were estimated by counting oxides on SEM images for a total area of 0·2 mm^2. The fact that the particles are oxides was verified using EDX and the sizes of particles therefore characterised were measured from SEM micrographs.

Because of the limited depth of the TIG remelted regions, 10 mm by 2 mm rectangular Charpy specimens with a 2 mm, 45° V notch (Fig. 1) were machined from the weld metal. Charpy impact toughness tests were carried out at 273 K using three specimens for each sample.

Results and discussion

Figure 2 shows that the number density of oxide particles decreased on remelting for all particle sizes. It is particularly evident that the larger particles have been greatly reduced by remelting (compare remelted with 350 ppmw O as welded sample). Note that only the 350 ppmw O sample was remelted: it is useful nevertheless to compare the 110 or 140 ppmw O as welded samples with the remelted sample which has a slightly lower oxygen content at 90 ppmw; the latter has a larger number density of oxide particles because the as welded samples have coarser oxides.

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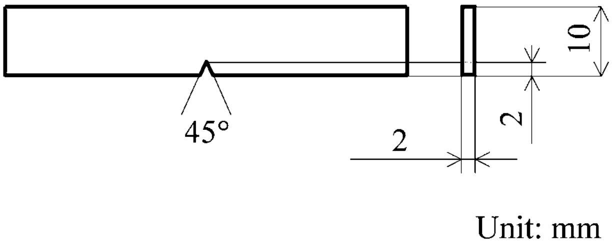
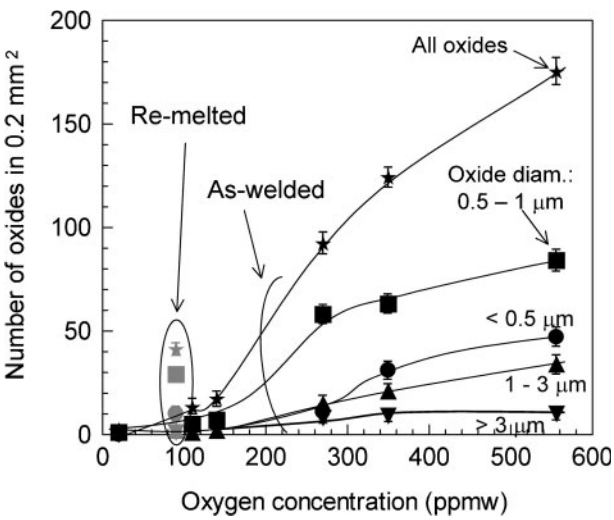
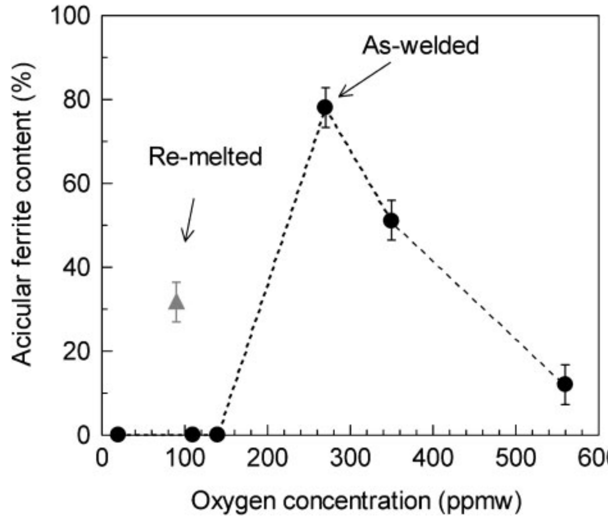


1 Schematic illustration of Charpy specimen tested



2 Number density of oxide particles as function of oxygen concentration



3 Acicular ferrite content as function of oxygen concentration

The microstructures of the as welded specimens have been comprehensively reported elsewhere[6] and that of the re-melted sample consisted of a mixture of acicular ferrite and martensite. Figure 3 shows both sets of data. It is interesting that fraction of acicular ferrite in the remelted sample has increased relative to the 560 ppmw O as welded sample. This is because the latter contains an excessive amount of oxides, beyond the optimum concentration determined in previous work on this system[6] (200 ppmw), therefore, its acicular ferrite content is limited by the prior formation of some allotriomorphic ferrite. The remelted sample on the other hand only contains acicular ferrite and martensite, resulting in a higher hardness, and yet has a better toughness, as illustrated in Figs. 4 and 5.

However, the improved toughness could be due to changes in acicular ferrite content rather than to oxide refinement. To resolve this, the data were analysed using a Bayesian neural network,[8,9] with the acicular ferrite content and mean oxide particle size as inputs and the toughness as the output. Figure 6 shows the perceived significance of both oxide size and acicular ferrite content on the toughness. This significance is akin to a partial correlation coefficient in ordinary regression: a greater value implies that the variable explains a greater fraction of the variation in toughness. The results confirm an important, independent role of oxide refinement in contributing to better toughness.

Summary

It is evident that in the context of arc welds, the refinement of oxide particles and a reduction in the total oxygen concentration from the usual hundreds of parts

Table 1 Chemical compositions of commercially available plate and wire used, wt-%

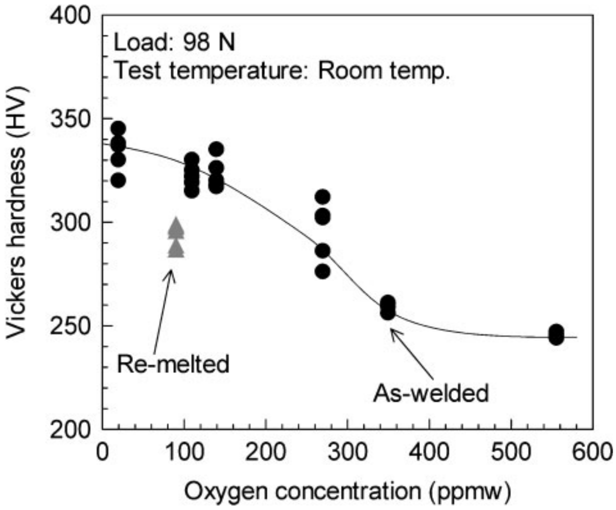
	C	Si	Mn	Cu	Ni	Cr	Mo	V	Nb	P	S
Plate	0·11	0·2	0·8	0·2	0·8	0·5	0·4	<0·01	<0·005	0·01	0·001
Wire	0·06	0·3	1·0	0·2	2·6	0·2	0·5	<0·01	<0·005	0·01	0·007

Table 2 Chemical compositions of as welded specimens and fraction *x* in shielding gas mixture $(1-x)$Ar–$x CO_2$, wt-%

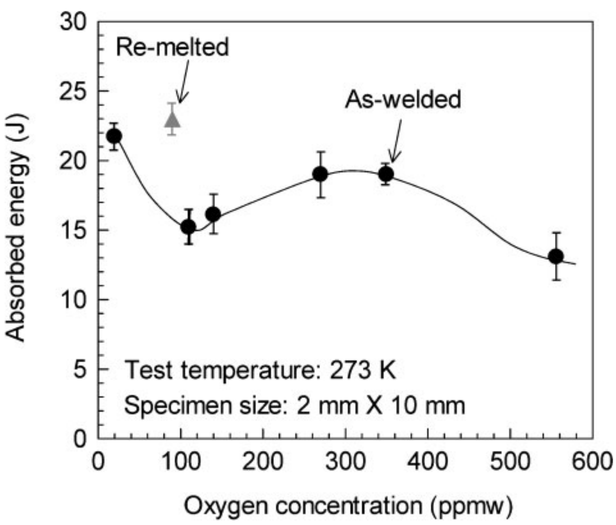
x	C	Si	Mn	Cu	Ni	Cr	Mo	V	Nb	P	S	O
0	0·07	0·3	1·0	0·2	2·4	0·2	0·5	<0·01	<0·005	0·01	0·005	0·002
0·01	0·07	0·3	1·0	0·2	2·4	0·2	0·5	<0·01	<0·005	0·01	0·005	0·011
0·02	0·07	0·3	1·0	0·2	2·4	0·2	0·5	<0·01	<0·005	0·01	0·005	0·014
0·1	0·07	0·3	1·0	0·2	2·4	0·2	0·5	<0·01	<0·005	0·01	0·005	0·027
0·2	0·07	0·3	1·0	0·2	2·4	0·2	0·5	<0·01	<0·005	0·01	0·006	0·035
1	0·07	0·3	1·0	0·2	2·4	0·2	0·5	<0·01	<0·005	0·01	0·006	0·056

Table 3 Chemical composition of remelted metal, wt-%

C	Si	Mn	Cu	Ni	Cr	Mo	V	Nb	P	S	O
0·07	0·2	1·0	0·2	2·3	0·2	0·4	<0·01	<0·005	0·01	0·004	0·009



4 **Vickers hardness as function of oxygen concentration**



5 **Charpy toughness as function of oxygen concentration**

per million, are beneficial to the toughness of strong weld metals. However, it is difficult to see how this can be achieved in practice.

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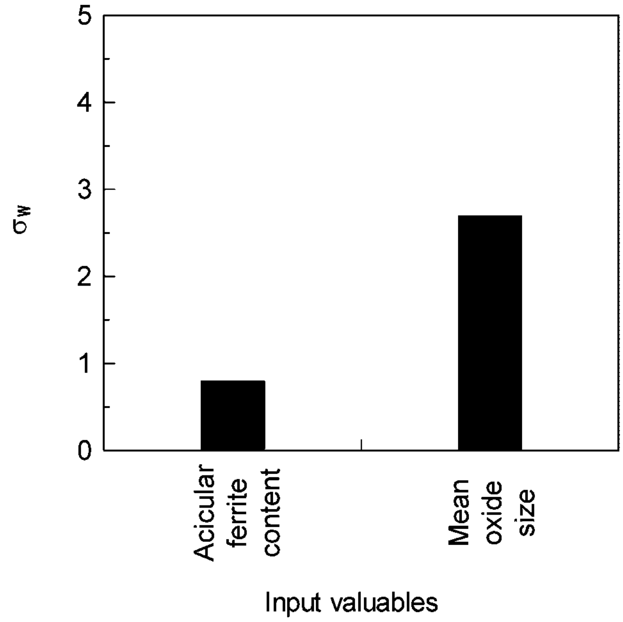

6 **Bar chart showing measure of model perceived significance σ_w of input valuables in influencing impact toughness**

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