THE EFFECT OF HEAT-AFFECTED-ZONE MICROSTRUCTURES ON FRACTURE TOUGHNESS OF DUPLEX STAINLESS STEELS

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ABSTRACT

The effect of heat-affected-zone (HAZ) microstructures on the impact energy of a duplex stainless steel (Zeron 100) has been examined. Different HAZ microstructures have been simulated using a weld thermal cycle simulator and the effects of varying heating and cooling times, particularly in the range 1250 to 800 °C, and the effect of the peak temperature have been examined with respect to resultant microstructures and toughness levels. The extreme variations in structure have been produced in order to understand the factors controlling the fracture behaviour of the HAZ regions.

INTRODUCTION

Duplex stainless steels offer good toughness, better corrosion protection, improved weldability and enhanced stress corrosion cracking resistance when compared to conventional stainless steels (Pertender et al (1), Eckenrod et al (2)).

The relationship between the weld and HAZ microstructures and mechanical properties is not yet well established. In addition to the ferrite/austenite phase balance, partitioning of alloying elements, phase morphology and grain size, the orientation and texture are important parameters controlling mechanical properties (Pickering (3), Solomon et al (4)). The HAZ microstructure is influenced primarily by the applied thermal cycle which is a function of welding variables. Complications arise in measuring the toughness of HAZ regions which are only one or two grain diameters wide. Despite the suggestion that HAZ toughness increases with austenite content the available data shows so much scatter (Gooch (5)) that the results are inconclusive. In this study specimens containing homogenous microstructures, produced by weld thermal cycle simulation, are used to model different regions of the HAZ and to establish a relationship between HAZ microstructure and toughness.

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EXPERIMENTAL TECHNIQUES

Zeron 100 (Fe-24.79Cr-7.318Ni-3.638Mo-0.645W-0.659Cu-0.191Si-0.659Mn-0.018C-0.2123N wt%) was supplied by Weir Material Services, Manchester. The 12.5 mm thick plate had been rolled and solution treated at 1150 °C followed by water quenching. The resultant microstructure contains rolled austenite bands in a ferrite matrix, Fig. 1. Standart Charpy specimens were cut from the plate and then simulated using a Smitweld thermal cycle simulator. They were subsequently machined with the notch perpendicular to the rolling direction. Cooling rate between 1250 and 800 °C, heating rate and peak temperature were varied on the basis of three dimensional heat flow equations modified for a disc source (Ashby et al (6)).

RESULTS AND DISCUSSION

Development of HAZ Microstructures, Simulations The schematic diagram showing the changes occuring in the HAZ of a typical duplex stainless steel is illustrated in Fig. 2. As temperature decreases below the melting temperature a two-phase field which is a mixture of $liquid + \delta$ is encountered. Below this partially melted zone, δ ferrite phase field exists, where the growth of ferrite grains take place rapidly. The final grain size will depend on the time spent between the δ ferrite solvus line and the peak temperature in the thermal cycle. During cooling from the δ ferrite phase to the $\delta + \gamma$ field austenite preferentially nucleates along the δ/δ grain boundaries. The austenite start temperature depends on chemical composition and on cooling rate. As temperature decreases, all grain boundaries become decorated by austenite allotriomorphs. In the later stages of cooling Widmanstätten type side plates and intragranular austenite can form, Fig. 3.

The δ ferrite grain size and the overall volume fraction of austenite are dependent on the thermal cycle for a given chemical composition. Delta ferrite grain size and volume fraction of austenite increase with high heat inputs (Fig. 3a) but the original austenite bands tend to be continuous or partially transformed at low heat inputs which also result in a relatively small delta ferrite grain size (Fig. 3b).

On the basis of microstructures observed in weld HAZ's, four different microstructural types were selected for simulations;

A - Partially transformed γ bands with limited δ grain growth;

B - Partially transformed γ bands with relatively large δ grains;

C - Completely dissolved γ bands, large δ grains, limited γ reformed during cooling;

D - Completely dissolved γ bands, large δ grains, much γ reformed during cooling.

Typical microstructures representing the simulations are given in Fig. 4. The *A* type microstructure is achieved with a high heating rate (250 $°Cs^{-1}$), low peak temperature (1250-1300 °C) and high cooling rate between 1250-800 °C ($\approx$ 5 seconds). As the peak temperature increases to between 1300-1350 °C the microstructure changes from *A* to *B* type. *C* and *D* type microstructures are obtained by decreasing the heating rate (20-40$°Cs^{-1}$), keeping the peak temperature around 1350 °C and selecting different cooling rates (5-20 seconds) so that the austenite transformation is controlled. Very large δ ferrite grains are obtained by holding the specimens at peak temperature for 20-60 seconds.

The Vickers hardness values of simulated samples are found to be much higher (300-340HV) than the as received condition (265HV). The combination of a relatively fine austenite grain size, non-equilibrium alloying element distribution and possible quenching stresses arising from simulation gives rise to high hardness values.

Impact Test Results An attempt has been made to correlate the Charpy impact energy with the volume fraction of phases and δ ferrite grain size. Impact energy as a function of δ ferrite volume fraction is plotted in Fig. 5. The result shows that there is no simple relationship despite the general belief that toughness decreases with increasing ferrite content. This is not surprising as the deformation behaviour of a duplex microstructure is complex and influenced by the individual deformation characteristics of each phase. For instance, the softer phase will tend to accommodate plastic deformation in preference to the hard phase. In the presence of ferrite and austenite phases, this is even more complicated because the strain hardening capacity of austenite is significantly higher than that of the ferrite (Wahlberg et al (7)). In the HAZ regions partitioning of alloying elements between the austenite and ferrite plays an important role in toughness as it can changes the relative strengths and the deformation behaviour of phases (7). Furthermore, the orientation of the microstructure with respect to a crack also has a dramatic effect on the toughness as the partially transformed austenite bands tend to be effective crack stoppers for propagation perpendicular to the rolling direction (4). A poor correlation is also observed between the impact energy and the delta ferrite grain size.

The toughness of the HAZ regions does not depend on the volume fraction of phases alone. The factors controlling the toughness (e.g. composition, grain size, distribution of phases) will be a function of heating rate, peak temperature and cooling rate (1250-800 °C). The heating rate and the peak temperature control the $\delta + \gamma \rightarrow \delta$ transformation and grain size of phases. The cooling rate controls the volume fraction of austenite which reforms. The compositions of the phases are also affected by these three parameters. A multiple regression analysis has therefore been carried out by taking into account the heating rate (HR), peak temperature (PT) and the cooling rate (CR) to obtain the following equation:

$$Impact\ Energy = 502.9 + 0.2187HR - 0.3008PT + 0.8731CR \qquad (1)$$

Good agreement is shown between experimental data and the data predicted using Eq. 1, Fig. 6. Eq. 1 indicates that toughness increases with increasing heating and cooling rates but decreases with increasing peak temperature. This is expected as the volume fraction of austenite increases with heating and cooling rates but the δ ferrite grain size increases with the peak temperature.

CONCLUSIONS

HAZ microstructures have been simulated successfully using the weld thermal cycle simulator representing the HAZ regions observed in real welds. The Charpy impact test results have shown that the variations in toughness values cannot be directly related to either volume fraction or grain size of individual phases. The analysis indicates that the toughness can be predicted by taking into account the heating rate, peak temperature and cooling rate (1250-800 °C) for a given composition.

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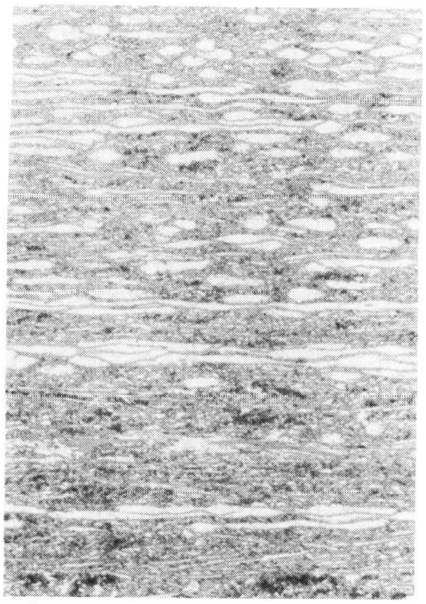

Fig. 1- As received microstructure, Austenite (white), Ferrite (grey).

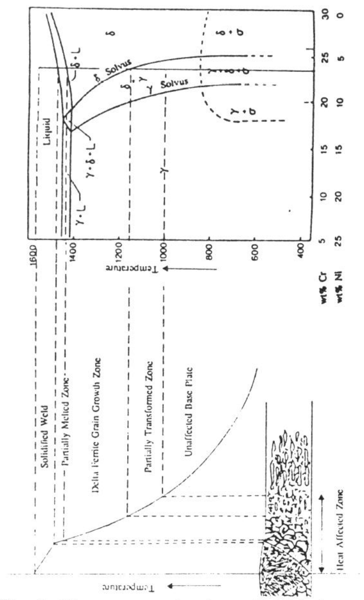

Fig. 2- Changes occuring in an HAZ (schematic).

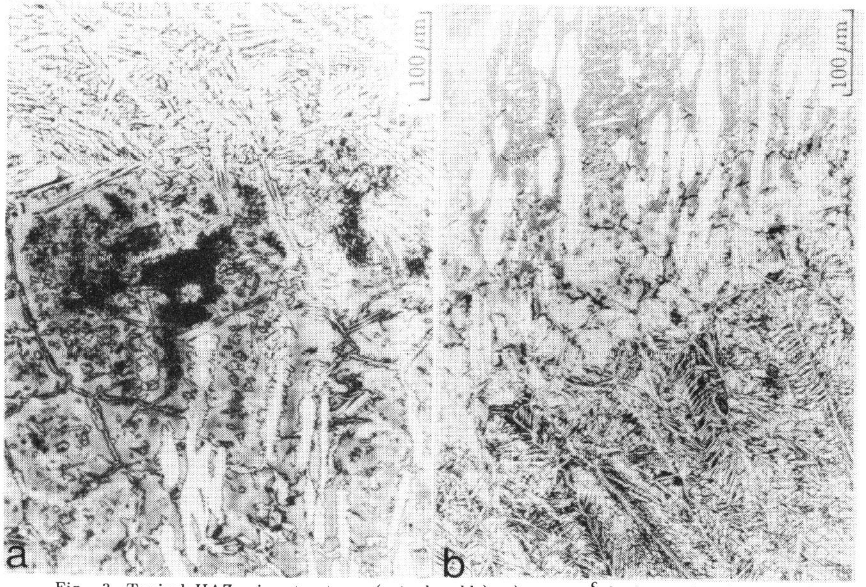

Fig. 3- Typical HAZ microstructures (actual welds), a) coarse δ ferrite grains, intragranularly nucleated austenite particles; b) relatively small δ ferrite grains, undissloved austenite bands.

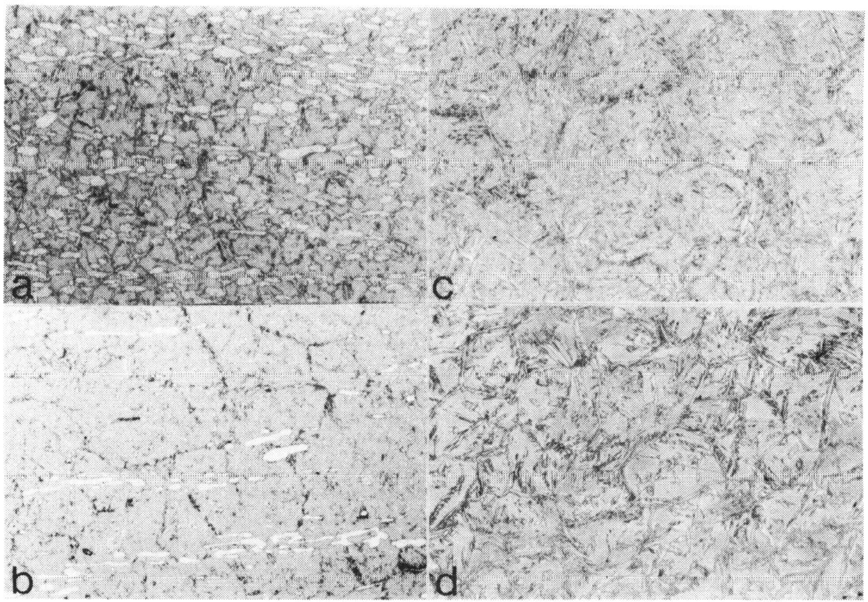

Fig. 4- Simulated HAZ microstructures, a) *A*; b) *B*; c) *C*; d) *D*.

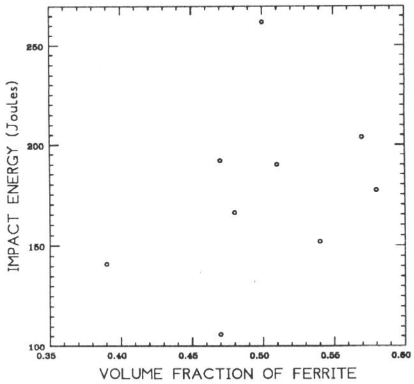

Fig. 5- Charpy impact energy versus volume fraction of ferrite.

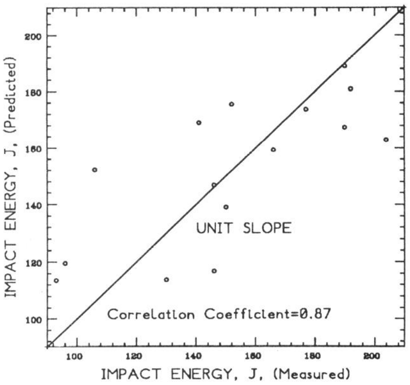

Fig. 6- Observed versus predicted impact energy values (Eq. 1).