Spot weldability of δ-TRIP steel containing 0·4 wt-%C

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Strong steels are usually difficult to resistance spot weld because of the tendency to form hard phases. This applies particularly to the transformation induced plasticity (TRIP) assisted steels with relatively high carbon equivalents. A new development in this context is the δ-TRIP steel, designed to retain δ-ferrite as a stable phase at all temperatures below melting. Fully martensitic regions are therefore avoided, making it possible to weld in spite of the high carbon concentration. The authors present here the first spot welding tests on the novel alloy system.

Keywords: Spot welding, Delta-ferrite, TRIP, Transformation plasticity

Introduction

Low alloy steels containing a microstructure in which the predominant phase is allotriomorphic ferrite, with a residue of bainitic ferrite and retained austenite, are used in the manufacture of automobiles.[1–6] The austenite can transform during deformation and delay the onset of plastic instability, thus endowing a good combination of strength and formability to these so called TRIP assisted alloys. A typical composition of such an alloy is Fe–0·15C–1·5Si–1·5Mn (wt-%); the steels are conventionally joined using spot welding.[7–9] There are typically 3000–5000 of these spot welds in the manufacture of a single automobile. The carbon equivalent of these alloys, and indeed of the strong dual phase steels,[10,11] is large when compared with interstitial free or bake hardening steels, making them more difficult to weld.[12,13] Special procedures in which a tempering pulse is applied to reduce the weld hardness have also been considered.[14–16]

A new class of steels with a reasonable chance of being exploited in the automotive industries has been designated δ-transformation induced plasticity (TRIP)[17,18] because δ-ferrite is retained from the solidification stage due to their high aluminium contents. With suitable design, the ferritic phase remains stable even at temperatures in excess of 1000°C so that rolling deformation is conducted in the two-phase $(\alpha+\gamma)$ region. The steel typically contains about 0·4 wt-% carbon and hence should in principle be difficult to spot weld. However, the persistence of ferrite in the microstructure should prevent the formation of fully martensitic microstructures in the regions affected by spot welding so it is possible that different criteria determine the weldability of the steel rather than a description based on just the carbon equivalent. These steels are strong and more ductile than the conventional TRIP assisted steels[3,4,19,20] so it would be particularly interesting to see whether they are weldable, which is the purpose of the present work.

Method and alloys

Alloy identifications are maintained to be the same as in the earlier work, where the manufacturing details are described.[18] Alloys 8 and 9 are new, incorporating a different balance between with respect to the silicon, aluminium and manganese concentrations. The alloys were manufactured as 34 kg ingots of $100\times170\times230$ mm dimensions using a vacuum furnace. The compositions are listed in Table 1. The physical metallurgy has been described elsewhere[17–19] but can be summarised as follows.

One problem with the alloy system is that the structure in the cast and rolled condition often does not follow the tenets of equilibrium;[18] the amount and stability of δ-ferrite is less than expected from a phase diagram calculation. As a result, the concentrations of elements which stabilise the δ-ferrite have to be exaggerated, which is why there are a number of alloys listed in Table 1. This has had an unexpected benefit in permitting the study of spot welding as a function of the stability of the δ-ferrite.

Spot welding tests were carried out under the conditions shown in Table 1 according to the common standards.[21–25] A dual phase steel DP-780[26] has in this work been compared with the experimental alloys; the DP-780 in its final state with a thickness of 1·8 mm has a yield strength of 480 MPa, ultimate tensile strength of 780 MPa and a total elongation of 24%. The squeeze, weld and hold times are conventionally expressed in cycles, where 1 s equals 60 cycles, corresponding to a 60 Hz frequency of the alternating current used. The 'up-slope' which describes the ramping of the voltage was zero, and all the welds were made using a single

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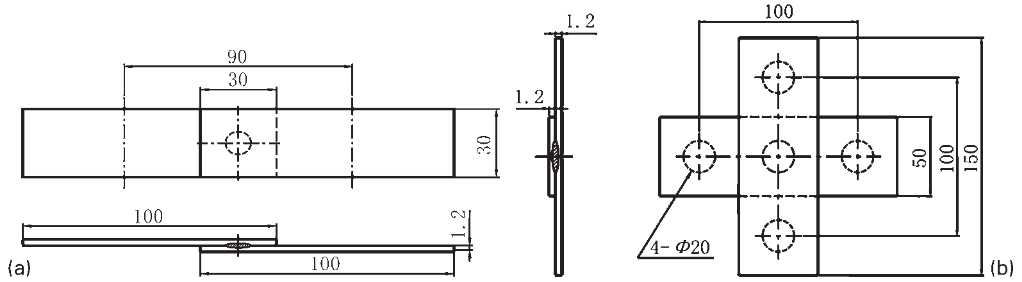
Published by Maney on behalf of the Institute
Received 16 May 2010; accepted 14 August 2010
DOI 10.1179/136217110X12813393169778



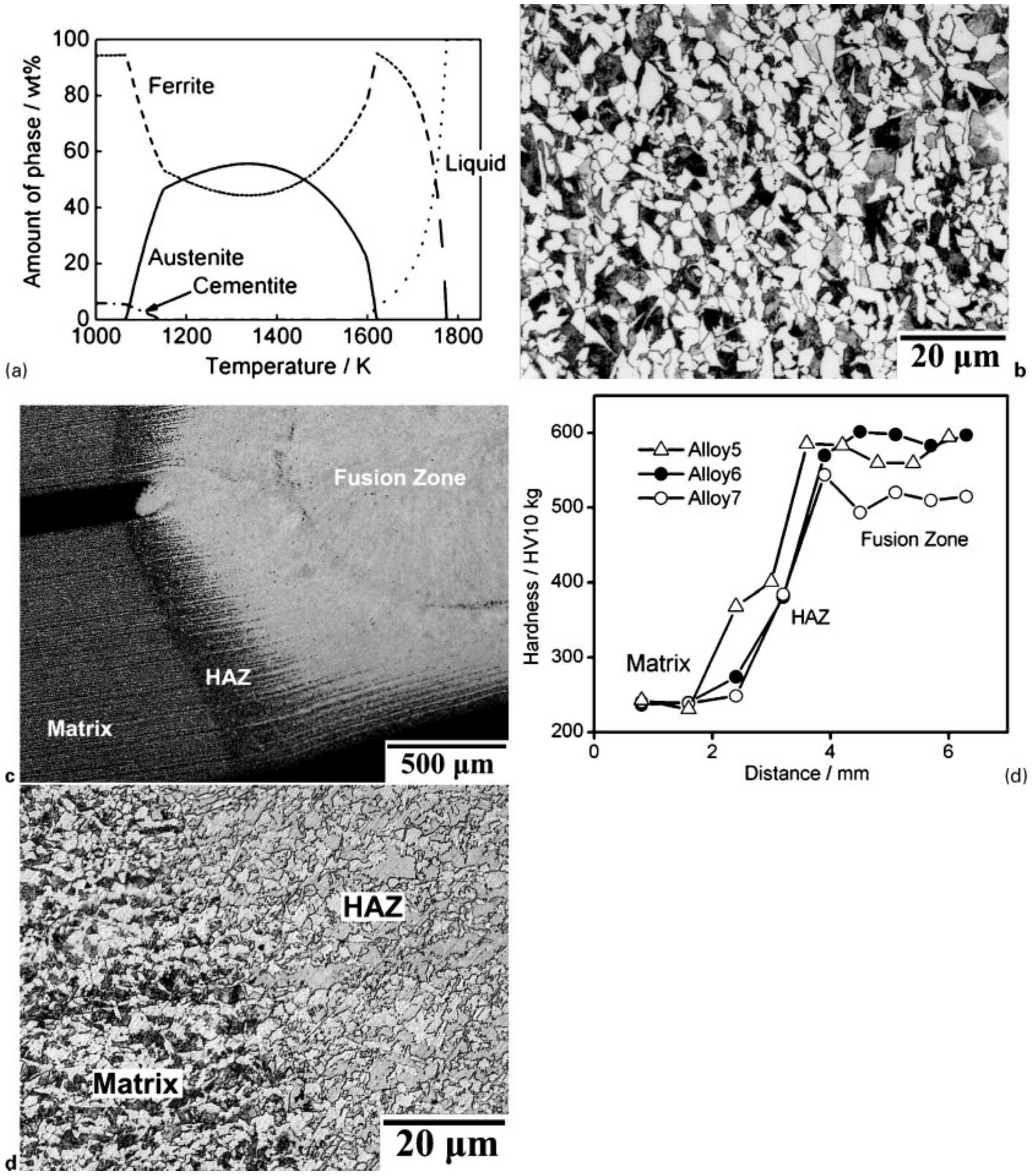
a shear tensile test samples; *b* cross-tensile test samples
1 Spot weld specimen geometries (dimensions in mm)

pulse. There was no imposed cooling. A Draper type electrode was used with a tip diameter of 6 mm.

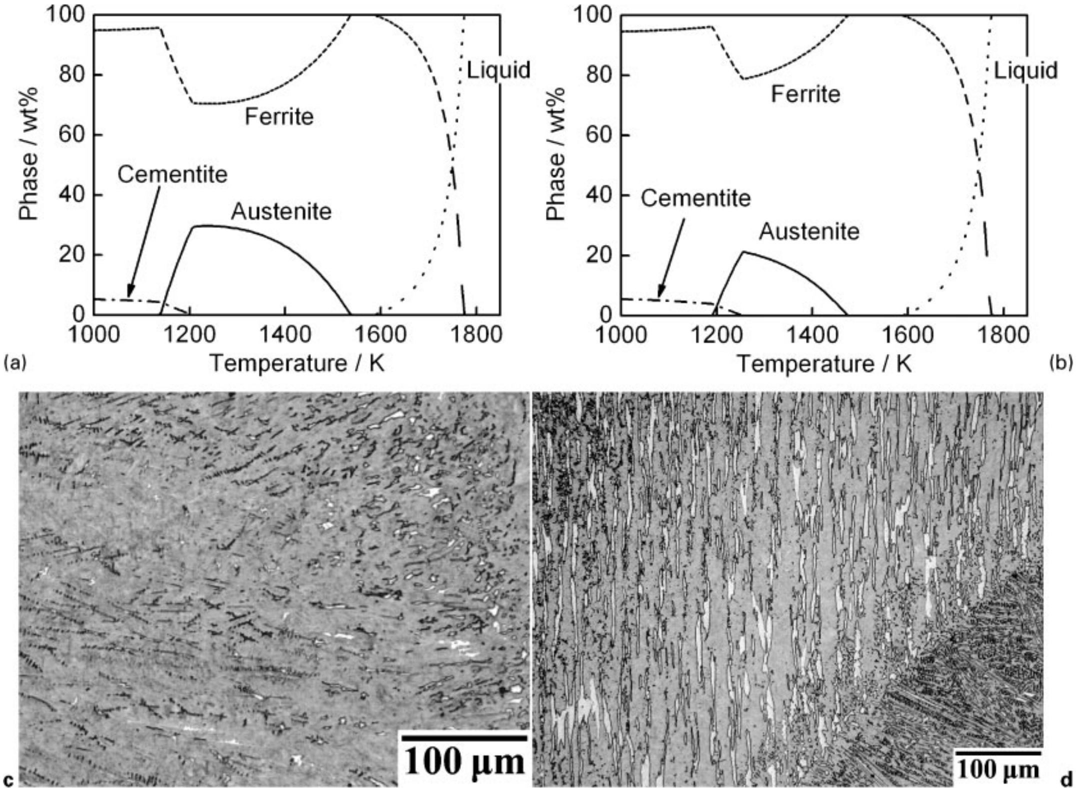
The shear tensile tests and cross-tensile tests specimens used and weld locations are shown in Fig. 1.

Results and discussion

Although equilibrium calculations indicate that Alloy 5 should at all temperatures contain at least 44 wt-% of



a calculated equilibrium phase fractions; *b* mixture of ferrite and pearlite following hot rolling into sheet form; *c* macrograph showing spot weld and surroundings; *d* distribution of hardness: results for Alloys 6 and 7 will be discussed later; *e* higher magnification image showing mixture of ferrite and martensite in HAZ
2 Alloy 5: untempered martensite etches light grey relative to allotriomorphic ferrite (white) and pearlite (dark)



3 ***a*, *b* calculated equilibrium phase fractions for Alloys 6 and 7 respectively and *c*, *d* structures of fusion zones of spot welds in Alloys 6 and 7 respectively**

ferrite (Fig. 2*a*), because the solid state transformation to austenite from δ-ferrite occurs without the required level of solute partitioning, the cast material is not in an equilibrium state.[18] In fact it becomes fully austenitic at 1100°C so that on cooling the hot rolled sheet,[27] the δ-dendrites present in the cast state are replaced by a mixture of allotriomorphic ferrite and pearlite as illustrated in Fig. 2*b*.

The fusion zone of the spot weld therefore transforms completely into austenite during cooling after solidification, and then into a fully martensitic state with a hardness of 577 ± 16 HV following rapid cooling (Fig. 2*d*). It is interesting, however, that much of the heat affected zone (HAZ) has a hardness less than that of martensite (Fig. 2*d*) because there is a mixture of allotriomorphic ferrite and martensite (Fig. 2) due to the high aluminium content which promotes the formation of ferrite.

The original intention of retaining δ-ferrite throughout the entire weld zone was not achieved with Alloy 5. While an overmatched nugget is beneficial to the mode of weld failure, an excessive weld nugget hardness can cause the crack that initiates between the sheets to be joined to follow a brittle path through the nugget.[28] So Alloys 6 and 7 were made using larger concentrations of the ferrite stabilising solutes Si and Al, as confirmed by the calculated phase diagrams and observations of the fusion zone in Fig. 3. Small quantities of δ-ferrite were

Table 2 Vickers hardness data*

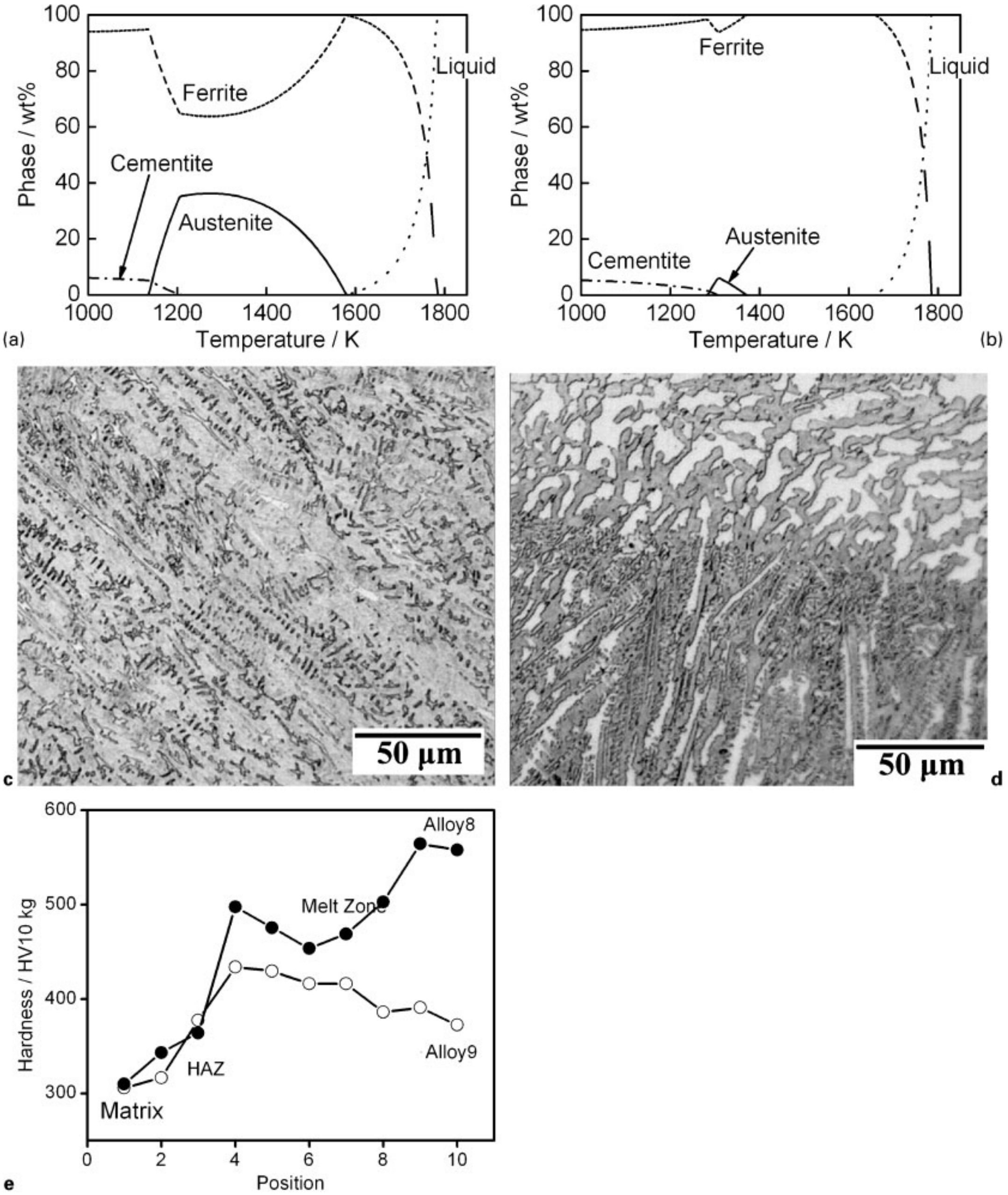
Alloy	Matrix	HV_{HAZ}	HV_{fused}	$\frac{HV_{fused}}{HV_{HAZ}}$
5	237 ± 6	385 ± 23	577 ± 16	2·43
6	250 ± 14	381 ± 18	590 ± 13	2·36
7	243 ± 5	384 ± 16	516 ± 18	2·12
8	328 ± 9	353 ± 10	524 ± 33	1·60
9	311 ± 6	347 ± 30	406 ± 22	1·31

*HV_{fused} represents hardness of the weld nugget.

Table 1 Compositions achieved during manufacture (wt-%) and other parameters related to spot welding*

	Alloy 5	Alloy 6	Alloy 7	Alloy 8	Alloy 9	Ref. 26
C	0·41	0·37	0·39	0·43	0·39	0·08
Si	0·26	0·76	0·77	0·20	0·21	1·39
Mn	1·53	1·53	1·50	0·52	0·51	1·75
Al	2·30	2·91	3·35	2·70	3·84	…
Cu	0·49	…	…	…	…	…
	HR	HR	HR	CR/HT	CR/HT	HT
Thickness, mm	1	1	1	1·2/2·5	1·2/2·25	1·8
Electrode force, kN	3·5	3·5	3·5	3·5/6	4·5/6	5·6
Squeeze time, cycles	40	40	40	40	40	…
Welding time, cycles	13	13	13/8	13/8	18	17
Hold time, cycles	13	13	13	13/30	10/30	25

*HR and CR mean hot rolled and cold rolled respectively; HT represents heat treatment described later in text.



4 ***a, b*** **calculated equilibrium phase fractions for Alloys 8 and 9 respectively,** ***c, d*** **structures of fusion zones of spot welds in Alloys 8 and 9 respectively and** ***e*** **distribution of hardness**

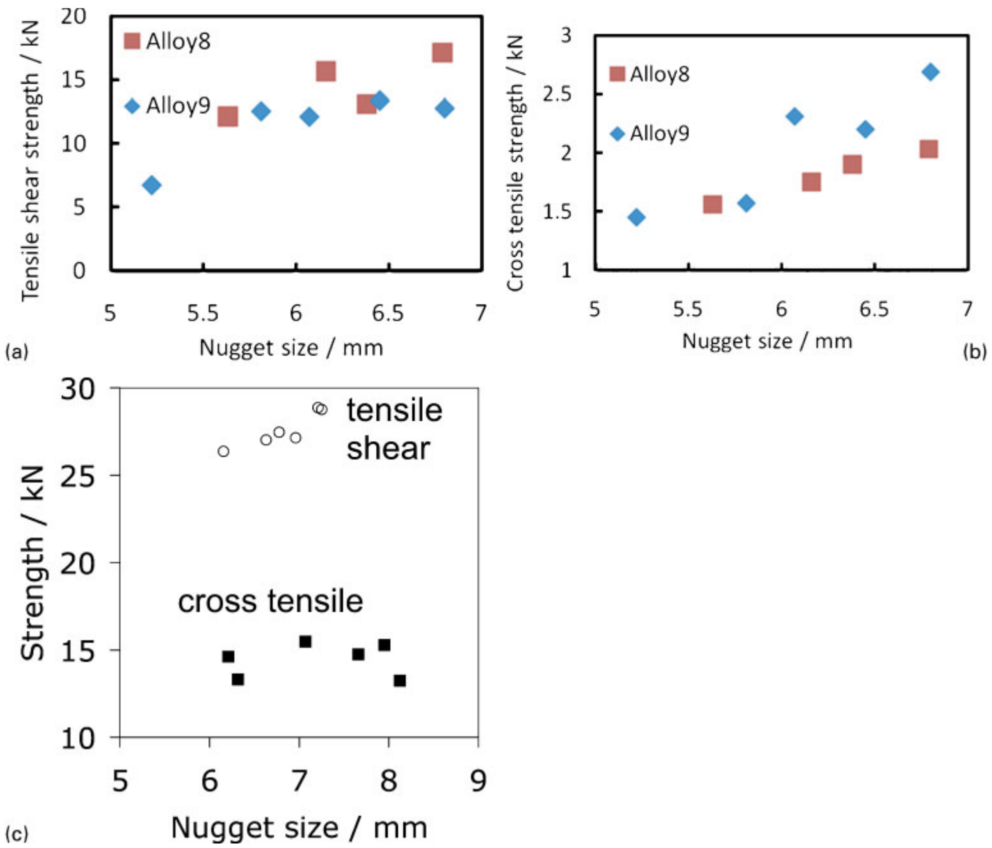
indeed retained in the fused region, leading to a minor reduction in the hardness for Alloy 7 which has more aluminium. To enhance the retention of δ-ferrite, the aluminium, silicon and manganese concentrations were adjusted again and resulted in dramatic reductions in the fusion zone hardness in Alloys 8 and 9. Considerable quantities of δ-ferrite were retained (Fig. 4) in spite of the fact that the cooling rate involved during spot welding is of the order of 1000–2000 K s^{-1}.[29]

Hardness data are summarised in Table 2. The results from mechanical testing are presented in Table 3 and Fig. 5 where the shear strength data are quite acceptable; the failure modes described as plug, partial and interface are illustrated in Fig. 6, where the former two

Table 3 Spot welds of as cold rolled sheets*

			Tensile shear strength		Cross-tensile strength	
Alloy	Current, kA	Nugget, mm	Maximum load, kN	Fracture	Maximum load, kN	Fracture
8	5·8	2·30	13·07	Partial	1·90	Partial
8	6·3	3·03	17·13	Partial	2·03	Partial
9	6·4	7·06	12·57	Plug	3·24	Interface
9	7·0	5·12	15·46	Partial	2·61	Partial

*The load is the maximum value recorded during the test.

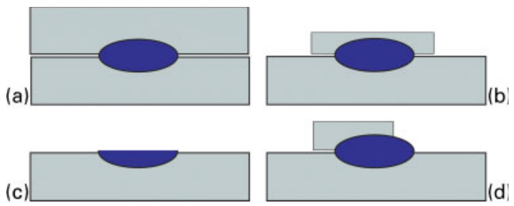


a tensile shear strength for 1·2 mm thick cold rolled alloys; *b* cross-tensile strength for 1·2 mm thick cold rolled alloys; *c* 1·8 mm thick 780 MPa cold rolled steel sheet

5 Strength as function of nugget size[26]

represent acceptable modes of failure. The cross-tensile strength is in all cases much lower than would be acceptable but this is not of concern because failure in all tests occurred in the base material which is in the cold or hot rolled condition rather than in the heat treated final state. The matrix or HAZ should be the tough zone in the δ-TRIP steels due to the dual phase microstructure. Fracture, however, happened in the matrix or HAZ in several cross-tensile tests in the welds of cold rolled sheet. This led to the poor welds because of the loss of ductility in the cold rolled condition.

Since the material is not destined for use in the cold rolled condition, samples were heat treated before spot welding in order to produce the microstructure consisting of δ-ferrite, bainitic ferrite and carbon enriched retained austenite.[19] The heat treatment consists of intercritical annealing at 900°C for 5 min followed by isothermal transformation in a salt bath at 410°C for 10 min and finally, cooling naturally in air. Spot welding with this starting microstructure gave promising results. The tensile shear strength of both alloys in the correct initial microstructural state is only about 5 kN less than the reference alloy at the same nugget diameter (Fig. 7); the reference alloy contains only 0·08 wt-% of carbon[26] compared with the 0·4 wt-% in the δ-TRIP alloys.



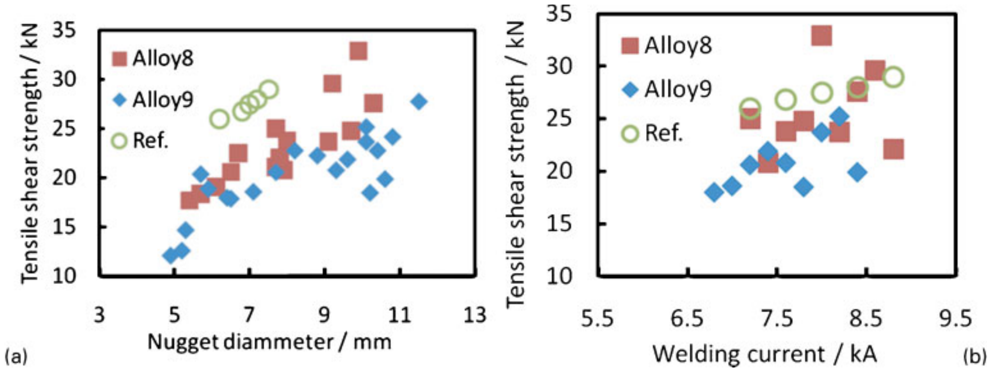
a intact spot weld; *b* plug fracture; *c* failure at interface between two sheets that are spot welded; *d* partial plug failure

6 Schematic illustration of spot weld failure modes

The current range over which the spot welds achieve good properties is, however, too narrow for practical purposes when performance is assessed in terms of the tensile shear strength (Fig. 7*b*) and failure mode. Attempts will therefore be made to understand the factors controlling the mode of weld failure, in order to redesign either the alloy or process for practical application. It is nevertheless clear that the spot weldability of δ-TRIP alloys containing 0·4 wt-% is reasonable and the work suggests that a further increase in the concentration of ferrite stabilising elements could lead to an acceptable window of welding parameters. Note also that the sheet thickness (1·2 mm) in the present work is greater than the typical 0·7 mm used in automotive manufacture, so future work will deal with thinner gauges.

Conclusions

It has been demonstrated that in spite of the large carbon concentration of δ-TRIP steel, it is possible to achieve a reasonable hardness distribution across a resistance spot weld if the alloying is such that ferrite persists in the microstructure at all temperatures. The effect of this ferrite is to reduce the hardness to manageable levels.



7 Tensile shear strength of spot welds of hot rolled sheets in heat treated condition, as function of *a* nugget diameter and *b* welding current

The properties and failure modes observed following spot welding are encouraging although they are not yet sufficiently robust for industrial application. The next stage in the development programme is to address this specific issue with a modification of the alloy design to encourage the retention of somewhat greater quantities of ferrite so that the maximum hardness falls to about 350 HV rather than the approximately 400 HV observed at present.

Acknowledgement

This work is partly supported by the World Class University Programme of the National Research Foundation of Korea, Ministry of Education, Science and Technology (project no. R32-2008-000-10147-0.

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