TECHNIQUES FOR IMPROVING THE WELDABILITY OF TRIP STEEL USING RESISTANCE SPOT WELDING

G Shi and S A Westgate
TWI Ltd, Cambridge, United Kingdom

ABSTRACT

High strength steels (UTS >600N/mm^2) are increasingly used to meet the severe requirements imposed by the automotive industry in terms of safety, reliability and reduction in gauge for energy saving. TRIP (Transformation Induced Plasticity) steels have become of considerable interest in recent years, because of their exceptional combination of high strength and ductility. In the work reported here, advanced resistance spot welding schedules were developed to achieve acceptable welds with improved static mechanical properties in thin sheet (1.05mm thick) 700N/mm^2 tensile strength TRIP steel. Improved resistance spot welding schedules were developed using up-slope and post heating current to reduce the cooling rate, or in-process tempering to reduce the hardness of the weld produced. Resistance spot welding of dissimilar steels was also carried out to examine the benefit of weld carbon reduction (i.e. reducing the carbon content of the weld nugget). The effects of material combination and process parameters on hardening, fracture mode and static mechanical properties of the joints (cross-tension and shear) were determined.

KEYWORDS

Resistance spot welding, TRIP steel, weld hardening, fracture mode, static mechanical properties.

INTRODUCTION

TRIP (Transformation Induced Plasticity) steels have become of considerable interest in the automotive industry in recent years because of their exceptional combination of high strength and ductility. Resistance spot welding is the main joining method for sheet steels in the automotive industry. The high carbon content of TRIP steels, coupled with fast weld cooling rates associated with these joining processes, leads to high hardness levels (up to 600HV) in the weld. When such welds are submitted to shear stress, a high joint strength can be achieved. However, when welds are submitted to peel or tension stress, the interface between the sheets acts as a notch and, due to the very hard weld nugget, brittle interface fracture is normally observed [1-3]. As a direct consequence, the strength of the weld decreases.

Modified resistance spot welding schedules, such as long weld times, to control cooling rates, and post-weld tempering [2,4-6], have been suggested to reduce weld brittleness in some high strength steels. These approaches are intended to reduce the cooling rate after welding or to temper the weld, so that a more ductile microstructure is achieved in the weld. When spot welding dissimilar steels, the weld metal carbon level is roughly the average of that of the two materials. Hence by welding a lower carbon steel to the relatively high carbon TRIP steel, a reduction in the proportion of martensite and its hardness in the weld nugget should reduce the hardness and brittleness of the weld itself.

In the work described here, modified resistance spot welding schedules were developed to achieve improved static properties in TRIP700 steel. The effect of process parameters and material combinations on the welding range and weld properties were examined.

1. EXPERIMENTAL WORK

1.1 Materials

Resistance spot welding trials were performed on 1.05mm thick electroplated zinc-coated (EZ) TRIP700 steel sheets. A 0.8mm thick hot dip zinc-coated (HDG) DP600 (dual phase) steel sheet was used for the dissimilar material combination. The chemical compositions of these steels are shown in Table 1.

Table 1 Chemical compositions (weight %) of the materials used

Steels	C	Si	Mn	S	P	Cr	Ni	Al	B
TRIP700	0.31	0.29	1.54	0.004	0.015	0.023	0.021	1.100	0.0004
DP600	0.12	0.19	1.58	0.003	0.011	0.450	0.009	0.047	0.0005

TWI analysis ref. S/01/356 and S/02/50

1.2 Equipment and Set-Up

Resistance spot welding trials were conducted on a single phase AC (100kVA) British Federal projection-welding machine with a 30kA short circuit current and a 10kN electrode force capacity. Welding current was recorded with a Miyachi printer current meter, type MM336A. Cu/Cr/Zr electrodes were to the standard ISO 5821 type B with a 6mm flat tip.

1.3 Resistance Spot Welding Schedules

Welding trials were carried out developing the following modified welding schedules to achieve the required weld nugget size, fracture mode and plug size in the TRIP700 steel:

- Resistance spot welding with controlled cooling, using up-slope and post-heating current (immediately after the weld time), to reduce the cooling rate and reduce the amount of martensite in the weld.
- Resistance spot welding with in-process tempering where the weld time is followed by a cool time to allow the transformation to martensite. Further resistance heating during the temper time then tempers the martensite to reduce its hardness.
- Resistance spot welding dissimilar materials (TRIP700 and DP600), to examine the influence of weld carbon reduction, i.e. reducing the carbon content of the weld nugget.

Squeeze time was set at 60 cycles (1.2s) to ensure full achievement of the welding force. Weld time was set at 14 cycles, and hold time was set at ten cycles throughout. The applied force was 4kN for all the trials. The welding parameters for the steels tested are shown in Table 2.

Weld growth curves were produced by pre-setting the electrode force and weld time, and then making welds at progressively increased current levels. The range of currents used was sufficient to define the limits of minimum weld size and weld splash. The minimum acceptable weld size was taken as 4√t (where t is the thickness in mm of the thinnest sheet in the combination). The effect of weld size on the cross-tension and shear strength of the weld was examined.

Table 2 Resistance spot welding parameters for TRIP700.

Spot welding schedule	Electrode force, kN	Up-slope time, cycles	Welding time, cycles	Cool time, cycles	Post-heat time, cycles
Baseline schedule	4	N/A	12	N/A	N/A
Baseline schedule with controlled cooling	4	10	12	N/A	5-50
Baseline schedule with in-process tempering	4	N/A	12	5-20	5-80
Welding of TRIP700 to DP600 with baseline schedule	4	N/A	12	N/A	N/A

N/A – not applicable

1.4 Static Mechanical Properties and Hardness of Welds

Cross-tension and shear tests were conducted to examine the static properties of the spot welded joints. Hardness distributions for selected welds were examined at a load of 1kg.

2. EXPERIMENTAL RESULTS

2.1 Resistance Spot Welding with Controlled Cooling

Controlled cooling methods are intended to permit some transformation of the austenite before the martensite start temperature, to reduce the proportion of martensite in the weld. It was found that interface and partial plug failures were dominant in the welds, as shown in Fig.1. The preferred full plug failures could not be achieved using the modified welding schedule with controlled cooling, although plugs of acceptable size could be produced at certain conditions (see Fig.1b).

a) TWI Image Ref:D004283-02

b) TWI Image Ref: D004283-01

Fig.1 Appearance of welds subjected to peel tests in 1.05mm EZ coated TRIP700, welded with 4kN electrode force, 12 cycles weld time and 6.7kA welding current (scale in mm):
a) Without controlled cooling - showing full interface failure, cracked on testing;
b) With controlled cooling of 10 cycles up-slope, 6.1kA post heating current and 30 cycles post heat time - showing partial plug failure.

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The post-heating current and post-heat time influenced both the weld nugget diameter and the plug diameter. Some conditions allowed plug diameters greater than the minimum acceptable 4√t to be achieved. Figure 2 shows the effect of the post-heating current and post-heat time on the weld nugget diameter and plug diameter. The post-heat parameters had a more significant effect on the fracture mode (weld plug diameter) than on the weld nugget diameter. Under constant post-heat times, the weld nugget diameter increased slightly with the increase in post-heating current, whereas a more significant increase in plug diameter was achieved (Fig.2a), indicating improved fracture mode. However, the weld still exhibited a partial plug failure mode even when a post-heating current of the same level as the welding current was used, as shown in Fig.2a.

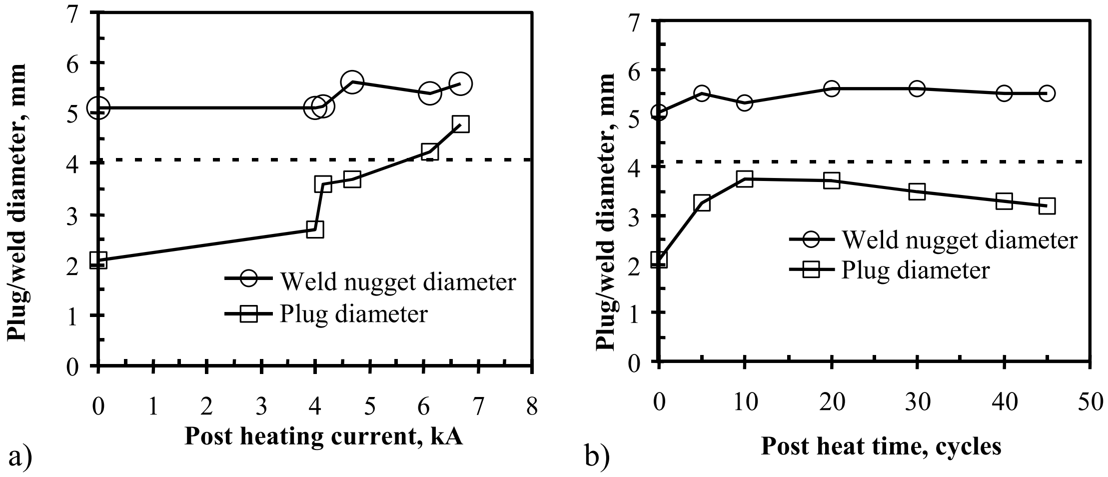

Fig.2 Effect of post heating current and post heating time on the weld diameter and fracture mode of welds in 1.05mm EZ coated TRIP700 welded with 4kN electrode force, 12 cycles weld time, 6.7kA welding current and 10 cycles up-slope:
a) Effect of post heating current at 20 cycles post heat time;
b) Effect of post heat time at 4.7kA post heating current.

The post-heat time had a similar effect on the weld nugget diameter to that of the post-heating current. The weld nugget diameter, produced using the baseline welding sequence, was about 5.0mm whereas the weld nugget diameter was increased to about 5.5mm when the post-heating was used, as shown in Fig.2b. However, plug diameters exceeding the minimum requirement could not be achieved.

In general, post-heating current had limited effect on the weld hardness at 20 cycles post-heat time, as shown in Fig.3a. The hardness was essentially unchanged at about 580HV even when the same current level as that of welding current was used for the post-heat.

The post-heat time also showed limited effect on the weld hardness, under constant post-heating current levels, as shown in Fig.3b. There was an optimised post-heat time for a given post-heating current in terms of reducing the weld hardening. For example, the weld hardness was slightly decreased when the post-heat time was increased from 10 to 20 cycles. However, the hardness level became higher when a post-heat time of 30 cycles, was used (Fig.3b).

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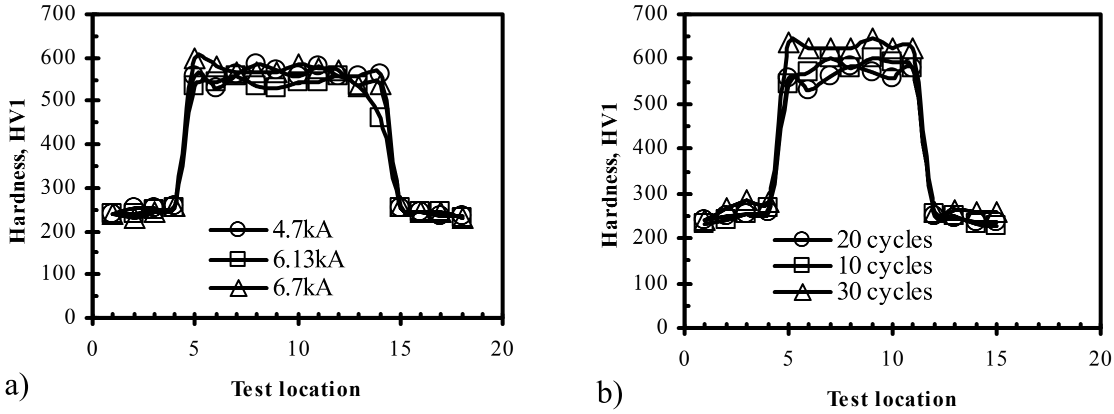


Fig.3 Effect of post heating current and time on the hardness profiles of welds in 1.05mm EZ coated TRIP700 welded using modified welding schedule with controlled cooling with 4kN electrode force, 12 cycles weld time, 6.7kA welding current and 10 cycles up-slope:
a) Effect of post heating current at 20 cycles post heat time;
b) Effect of post heat time at 6.1kA post heating current.

The cross-tension and shear strengths of spot welds, produced with the same electrode force, welding current and weld time but with various post-heating current levels and post-heat times, are shown in Fig.4a and 4b. The data points in these figures show the individual failure loads from three samples produced at each welding condition. The failure loads in cross-tension and shear varied slightly depending on the post-heating current and post-heat time, at the selected electrode force, welding current and weld time.

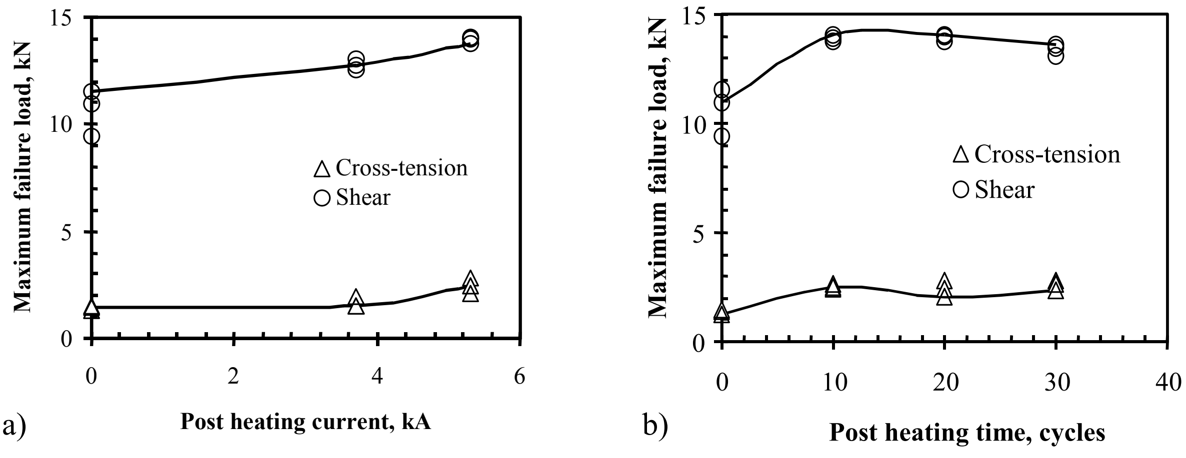


Fig.4 Effect of post heating current on the static mechanical properties of welds in 1.05mm EZ coated TRIP700, welded using modified welding schedule with controlled cooling with 4kN electrode force, 12 cycles weld time, 6.7kA welding current and 10 cycles up-slope:
a) Effect of post heating current at 20 cycles post heat time;
b) Effect of post heat time at 6.10kA post heating current.

Figure 4a shows the effect of the post-heating current on the cross-tension and shear failure loads for welds produced using the same parameters in the baseline welding sequence, plus ten cycles up-slope and 20 cycles post-heat time. The weld shear strength increased approximately linearly with increase in the post-heating current. The weld shear strength was about 35% higher and the weld cross-tension strength was about 75% higher than those of welds produced without post-heat, when a post-heating current of 5.3kA (80% of the welding current) was used.

Figure 4b shows the effect of the post-heat time on the cross-tension and shear failure load of the weld. The highest weld strength did not appear to be achieved in welds produced with the longest post-heat time. The joint strength increased with increase in post-heat time up to 20 cycles, with a post-heating current of 6.1kA. Further increase in post-heat time gave no additional benefit.

2.2 Resistance Spot Welding with In-Process Tempering

Welding trials with in-process tempering were conducted with different tempering current levels and temper times. The effect of the tempering current and temper time on the weld nugget diameter and plug diameter is shown in Fig.5. These welds were produced using the same electrode force, welding current and weld time. The welds produced with lower tempering current levels or shorter temper time had partial plug failures. The plug diameter increased with the increase in either tempering current or temper time. For a given tempering current, there was a critical temper time above which the weld exhibited full plug failures. This critical time decreased with the increase of tempering current, as shown in Fig.5 (e.g. about 80cycles at 4.0kA and 25cycles at 4.9kA).

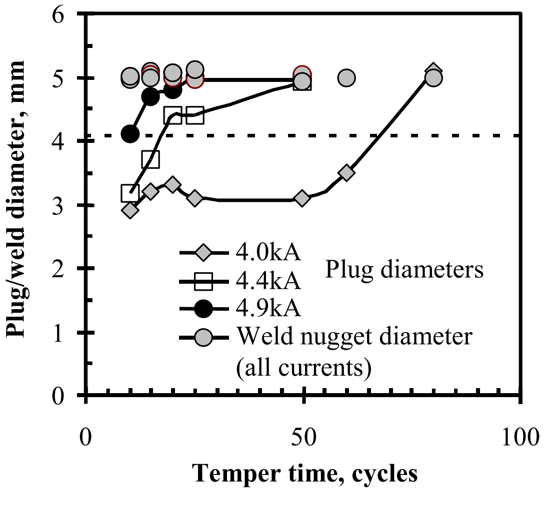


Fig.5 Effect of post heat time, at different levels of post heating current, on the plug diameter and weld diameter of welds in 1.05mm EZ coated TRIP700, welded with 4kN electrode force, 12 cycles weld time, 6.6kA welding current and 20 cycles cool time.

The effect of the cool time on the weld plug diameter is shown in Fig.6. There was no benefit from the tempering when cool time was less than 20 cycles, as insufficient time was allowed for the initial transformation to martensite. Consequently, martensite only formed during cooling after the end of the temper time. When the cool time was longer than 20 cycles, the martensite formed and was tempered as intended, to permit partial plug and full plug failures to be achieved on testing.

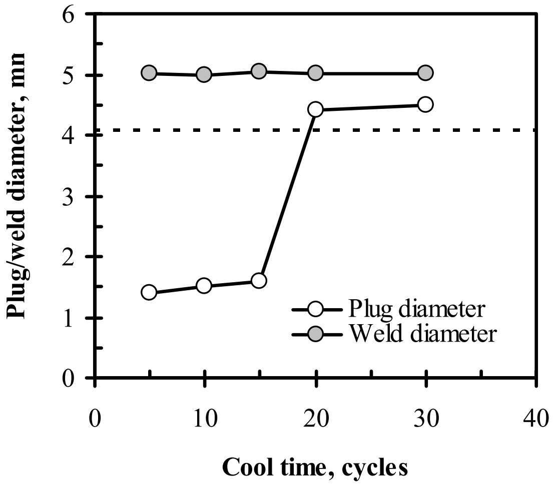
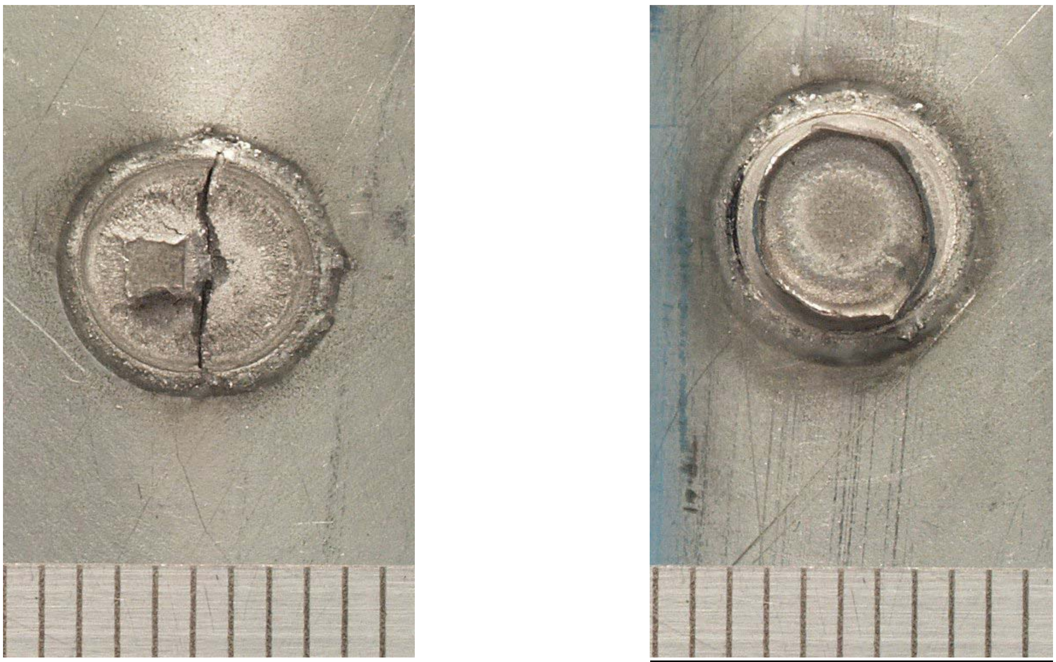


Fig.6 Effect of cool time (prior to in-process tempering) on the plug diameter and weld diameter of welds in 1.05mm EZ coated TRIP700, welded with 4kN electrode force, 12 cycles weld time, and 6.6kA welding current, 4.4kA tempering current and 25 cycles temper time.

The effect of the temper treatment on the fracture appearance of peel tested samples is shown in Fig.7. The weld produced using the baseline welding sequence exhibited a partial plug failure mode (Fig.7a), whereas the weld produced using in-process tempering had a full plug failure mode (Fig.7b).



a) TWI Image Ref:D004081-09

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Fig.7 Appearance of welds subjected to peel tests in 1.05mm EZ coated TRIP700 welded with 4kN electrode force, 12 cycles weld time, 6.6kA welding current and 10 cycles hold time (scale in mm):
a) Without in-process tempering - showing mainly interface fracture, cracked on testing;
b) With in-process tempering of 20 cycles cool time, 4.9kA tempering current and 25 cycles temper time - showing complete plug fracture.

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The effect of temper time on the hardness profiles of welds produced using the modified welding schedule with in-process tempering is shown in Fig.8. The weld hardness was significantly reduced, from about 580HV to about 400HV, by in-process tempering, using 25 cycles temper time and 4.4kA tempering current, as shown in Fig.8.

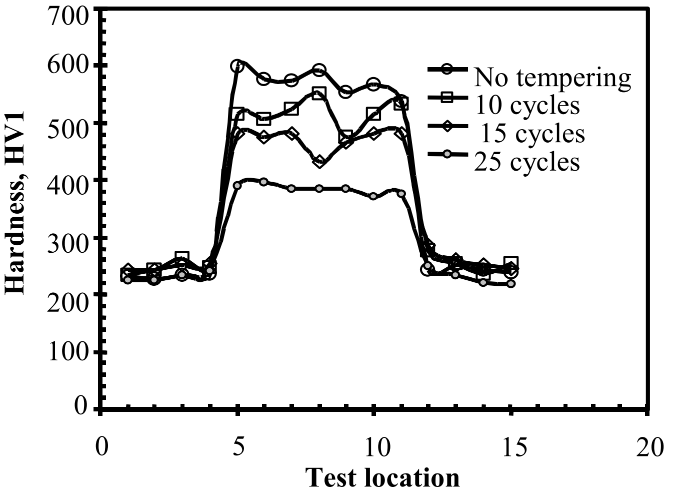

Fig.8 Effect of temper time on the hardness profiles of welds in 1.05mm EZ coated TRIP700, welded using modified welding schedule with in-process tempering with 4kN electrode force, 12 cycles weld time, 6.7kA welding current, 20 cycles cool time and 4.87kA tempering current.

The cross-tension strength and shear strength of spot welds, produced with the same electrode force, welding current and weld time, but with various tempering current levels and temper times, are shown in Fig.9a and 9b. The data points in these figures represent the peak failure load from three different samples produced at each welding condition. The weld strength in cross-tension and shear again varied depending on the tempering current and temper time.

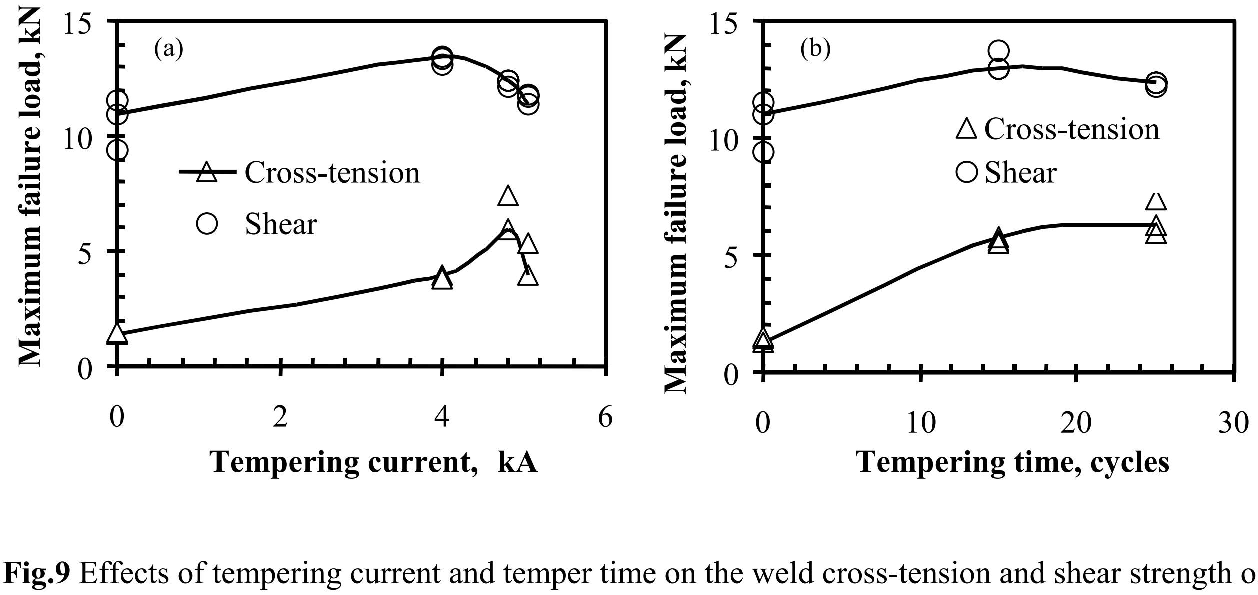

Fig.9 Effects of tempering current and temper time on the weld cross-tension and shear strength of welds produced using the modified welding sequence with in-process tempering. 4.0kN electrode force, 6.7kA welding current, 12 cycles weld time and 20 cycles cool time.
a) Effect of tempering current (25 cycles temper time);
b) Effect of temper time (4.8kA tempering current).

The cross tension strength increased with increase in post-heating current up to 4.5kA at a tempering time of 25 cycles, and was up to four times higher than that of welds produced using the baseline welding sequence (see Fig.9a). At this current, shear strength was beginning to fall again after an initial 25% rise. Similar trends were found in the effect of the tempering time on the weld strength, as shown in Fig.9b. A tempering time of 15 to 25 cycles gave a substantial increase in cross tension strength and a slight increase in shear strength. Full plug failure mode was associated with these higher strength welds.

2.3 Resistance Spot Welding TRIP700 to DP600

A weld growth curve was produced to determine the suitable welding current range for spot welding TRIP700 to DP600 at the selected welding conditions, as shown in Fig.10. The current range, from the minimum current required to give a nugget diameter of 4√t to the current resulting in the onset of splash, was adopted as the welding current range. The welds were produced using the baseline welding sequence. This indicated that a welding current range larger than 1kA above the minimum required size (4√t) could be achieved with full plug fractures for the TRIP700 to DP600.

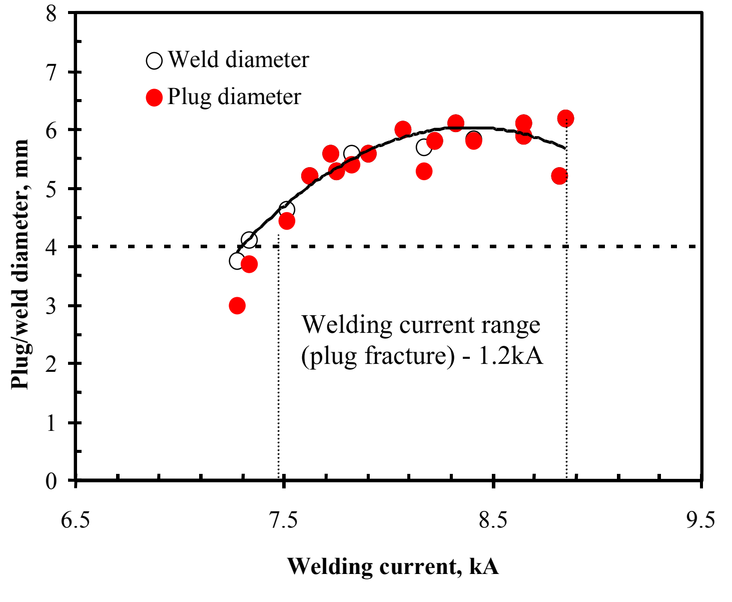

Fig.10 Growth curve for welds between 1.05mm EZ coated TRIP700 and HDG coated 0.8mm DP600, welded with 4kN electrode force and 12 cycles weld time. Weld diameter is the apparent fused zone size or full plug size. In the case of a partial plug failure, the plug size is also indicated.

The cross-sections of a 4√t weld and a maximum size weld near splash are shown in Fig.11. The hardness within the weld nugget was about 500 to 550HV, which was only slightly lower than that of the weld in the TRIP steel welded using the baseline schedule (i.e. 550 to 600HV). The hardness decreased slightly with the increase of welding current.

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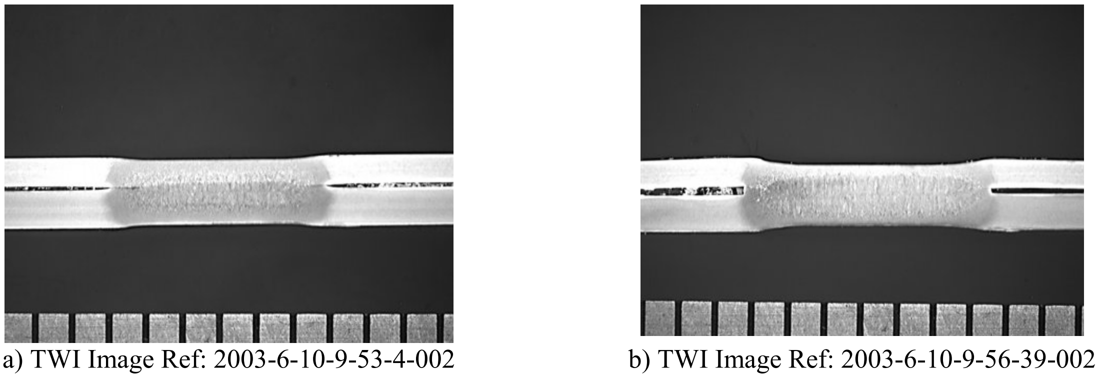

Fig.11 Cross sections of welds between 1.05mm EZ coated TRIP700 and HDG coated 0.8mm DP600, welded with 4kN electrode force and 12 cycles weld time (scale in mm):
a) 7.2kA welding current;
b) 8.2kA welding current.

The effect of weld nugget size on the cross-tension and shear strength of the welds is shown in Fig.12a and 12b. These welds were made at three current levels, to produce nominally 5√t welds, the maximum size without weld splash and welds with splash. At each condition, three welds were tested and the peak failure load from each sample is shown in these figures.

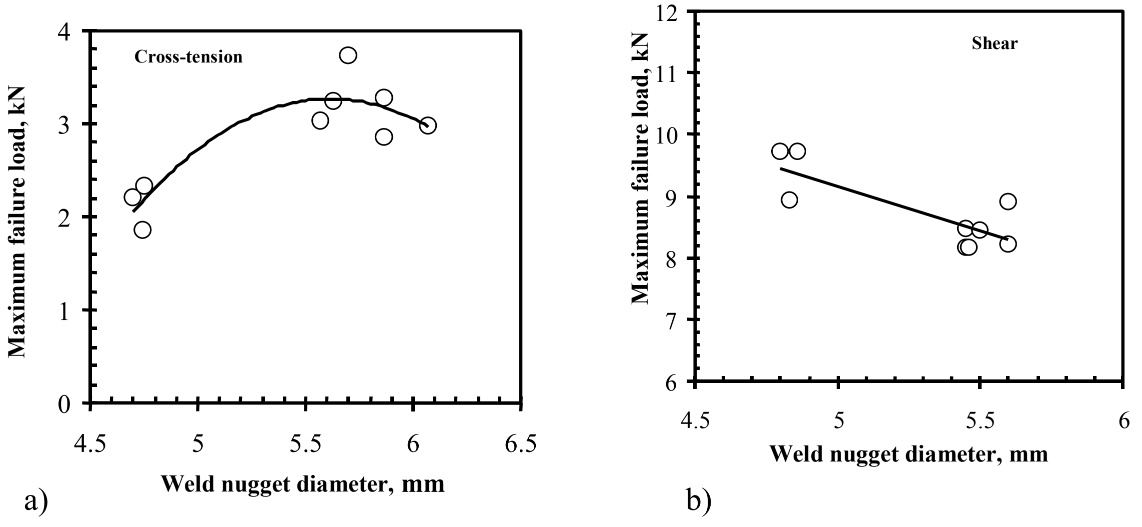

Fig.12 Relationship between the weld static strength and weld nugget size in welds between EZ coated 1.05mm TRIP700 and HDG coated 0.8mm DP600:
a) Cross-tension;
b) Shear.

The cross-tension strength increased with increase in weld nugget diameter but decreased slightly when weld splash occurred, as shown in Fig.12a. The fracture occurred in the TRIP700 in all cases, despite being slightly thicker and stronger than the DP600. Despite the occurrence of plug failure, the failure loads were only about 30% of the shear failure loads (Fig 12b). In addition, the cross tension failure loads were better than those achieved in the TRIP steel but only about 60% of those achieved in DP600 to itself [1].

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The shear strength decreased slightly with the increase in weld nugget size, as shown in Fig.12b. The fracture occurred in both sheets for the 5√t welds but just in the DP600 (which showed greater deformation in peel than the TRIP700). This may be related to a softening of the material around the weld or greater electrode indentation with the larger weld nugget sizes.

3. DISCUSSION

3.1 The Effect of Cooling Rate

The cooling rate of the weld, in the baseline resistance spot welding sequence, is very high due to the accelerated cooling effect of the water-cooled copper electrodes. It has been shown for resistance spot welding [7] that the time to cool over the temperature range 900 to 300ºC could be as short as 0.2s, and only slightly longer if the hold time was short and the electrodes were quickly raised. The incubation time for the bainite nose in the calculated time-temperature-transformation (TTT) diagram of TRIP700 is longer than one minute [8]. This results in the formation of a martensite dominated microstructure in welds in TRIP steels. The results show high hardness and brittle welds are produced, which give interface failures and particularly low cross-tension strength.

3.1 Modified Welding Sequences

Longer weld times or the use of a lower current, post-heat pulse immediately following the weld pulse, are designed to reduce the cooling rate to prevent excessive martensite formation. This controlled cooling approach gave a slight benefit, as the weld cross-tension and shear strengths could be improved by some 25-30%. However, it had little effect on the weld hardness and fracture mode using the selected parameters. Also, the improvement was probably partly related to the slight increase in weld nugget size (about 10%).

The in-process tempering schedule was effective in reducing the brittleness of welds in TRIP700. Weld hardness was significantly reduced (from about 600HV to 400HV) and the cross-tension strength was increased by up to a factor of four, when using the conditions developed in this work. A cross-tension strength of up to 50% of the shear strength could be achieved, and the shear strength itself was improved by up to 25-30%. The weld fracture mode was changed from the brittle interface failures to the preferred full plug failures. However, it should be noted that the use of suitable cool time, tempering current and temper time was critical to achieve the best results in terms of weld strength, fracture mode and process efficiency. Insufficient cool time prevents the full transformation to martensite, allowing it to form on final cooling at the end of the temper pulse. Insufficient temper time or current gives insufficient hardness reduction of the martensite. However, too long a temper time or too high a current allows retransformation to austenite, and martensite will again form on final cooling.

It should be noted that these improvements were achieved by in-process tempering with an increase of the sequence time of each weld by up to 45 cycles (0.9s), depending on the welding parameters selected. Longer times may be required for thicker material. Furthermore, in-process tempering schedules would need to be set up to give reliable results, depending on the material and thickness combinations being welded and the benefits achieved may be sensitive to other production variables.

3.2 Weld Carbon Reduction

Weld carbon reduction, by introducing a low carbon steel interlayer, has proved effective in reducing the weld brittleness in some transformation hardened high strength steels [4]. Current work found that virtually full plug failure could be achieved over a reasonable welding range (1.2kA), when TRIP700 was resistance spot welded to DP600. This was achieved despite only a slight (10%) hardness reduction in the weld nugget, and no reduction of the HAZ hardness in the TRIP steel. The shear strength was slightly lower than that of the welds in TRIP700 to itself but similar to that of the welds in DP600 to DP600. Conversely, the cross tension strength was higher than that of the welds in TRIP700 to itself but lower than that of the welds in DP600 to DP600 [1].

4. CONCLUSIONS

- In-process tempering was effective in reducing the brittleness of spot welds in TRIP700. Weld hardness was reduced from about 600HV to about 400HV and the welds exhibited full plug failures. The cross-tension strength of welds was up to four times higher than that of welds produced without tempering and the shear strength could also be improved by 25-30%.
- In-process tempering required an increase in sequence time of typically 0.9s was required for the schedule to be effective for the 1.05mm material, and the results may be sensitive to other process variables
- Controlled cooling schedules, using up-slope and a post-weld current pulse, had limited effect on the reduction of brittleness of welds in TRIP700. Although cross-tension strength could be improved by 75% and shear strength was increased by 25%, compared to the baseline sequence, little reduction in weld hardness was achieved and full plug failures could not be reliably achieved.
- Welds between TRIP700 and DP600 gave acceptable plug failures, despite little reduction in weld hardness. The shear strength of welds was similar to those in DP600 to itself but cross-tension strengths were substantially lower.

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