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Effect of Resistance Spot Welding Parameters on the HAZ Softening of DP980 Ferrite-Martensite Dual Phase Steel Welds

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Abstract: HAZ softening (i.e. reduction of HAZ hardness in respect to base metal) plays an important role in mechanical properties of dual phase steel resistance spot welds. Generally, HAZ softening can improve RSW mechanical performance in terms of load bearing capacity and energy absorption capability via promoting PF mode at smaller FZ size. This paper addresses the effect welding parameters, viz. welding current, welding time and electrode force on the minimum hardness in HAZ of DP980 resistance spot welds. A parameter, so called heat factor, is defined to explore the effect of welding heat input on the degree of HAZ softening.

Key words: Resistance spot welding · Dual phase steel · HAZ softening · DP980

INTRODUCTION

Ferrite-martensite dual phase (DP) steel is one of the most common AHSS steels which is currently used in automotive industry [1]. Usually ferrite–martensite DP steels are produced by intercritical annealing followed by rapid cooling. During the intercritical annealing small pools of austenite are formed in the ferrite matrix, which subsequently transform into martensite upon rapid cooling [2]. In this combination of two phases, martensite contributes with high strength and ferrite matrix provides good elongation that can produce a good combination of strength and ductility for applications which required good formability. This unique composite microstructure offers other interesting mechanical properties such as continuous yielding, low yield stress to tensile strength ratios and high initial work-hardening rate [3-5].

Weldability of DP steels is one of the key factors governing their application in the automotive industry. Resistance spot welding is the predominant process in sheet metal joining particularly in the automotive industry. Vehicle crashworthiness, which is defined as the capability of a car structure to provide adequate protection to its passengers against injuries in the event of a crash, largely depends on the integrity and the mechanical performance of the spot welds [6-8]. Energy absorption capability is an important parameter in vehicle crashworthiness which in turn is affected by microstructure of the material. Due to welding thermal cycle the designed microstructure of the AHSS is destroyed.

Microstructure development during RSW is significantly affected by base metal (BM) chemistry, initial microstructure of BM and the high cooling rates inherent to RSW process [9]. It is reported that the cooling rate during RSW changes from roughly 3000 °C/s for 2.0 mm thickness to over 10^5 °C/s for thicknesses less than 0.5 mm [10]. These cooling rates are sufficient for producing martensite in fusion zone of dual phase steels and even in low carbon steels. HAZ softening (reduction of hardness of the HAZ in respect to BM) due to martensite tempering is also reported in some grades of AHSS during RSW (i.e. DP780, DP980 and martensitic grades) [11-13]. This complex microstructure development can impact the failure behavior of AHSS RSWs and therefore, the effects of welding on the crash performance should be investigated.

One of the interesting phenomena during RSW of dual phase steels is the HAZ softening (i.e. reduction of HAZ hardness in respect to BM). It has been determined that HAZ softening is a very complex phenomenon and is affected by: microstructure martensite content, steel chemistry, heat input and prestrain. [14-18] The potential hardness difference between the softened HAZ and the base material is proportional to the steel martensite content [15, 16]. Steel alloy content can decrease HAZ softening by impeding the softening rate [17, 18]. Increasing heat input (increasing the ratio of welding power to travel speed) increases HAZ softening as the local temperature of the subcritical HAZ is elevated for longer times, further advancing the tempering reaction.

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Table 1: Chemical composition of the DP980 used in this study (%wt)

	C	Mn	Si	Cr	Mo
DP980	0.14	1.7	0.08	0.25	0.16

Table 2: Welding schedules

Welding Current (kA)	7-8-9-10-11-12
Welding Time (sec)	0.2-0.3-0.4-0.5
Electrode Force (kN)	4-4.5-5
Holding Time (s)	0.2
Squeeze Time (s)	0.4

Finally, prestrain has been seen to increase the overall magnitude of HAZ softening while increasing the absolute hardness of the softening region.

HAZ softening plays an important role in mechanical properties of DP steels, if any [19]:

- HAZ softening improves interfacial to pullout failure transition. It has been shown that DP980 spot welds has lower tendency to interfacial failure in comparison with DP780, despite its higher BM and FZ strength.
- HAZ softening enhanced overall ductility of the spot welds.
- Generally, HAZ softening can improve RSW mechanical performance in terms of load bearing capacity and energy absorption capability via promoting PF mode at smaller FZ size.

This paper aims at investigating the factors controlling HAZ softening in DP980 resistance spot welds.

EXPERIMENTAL PROCEDURE

1.5 mm thick DP980 dual phase steel was chosen for this study. The chemical composition of the steel is given in Table 1. Spot welding was performed using a 120kVA AC pedestal type resistance spot welding machine operating at 50 Hz, controlled by PLC. Welding was conducted using a 45-deg truncated cone RWMA Class 2 electrode with an 8-mm face diameter. To study the effects of weld FZ size on failure mode, spot welding was performed in different welding conditions. Welding schedules are given in Table 2.

Samples for metallographic examination were prepared using standard metallography procedure. Weld microstructures and macrostructures were examined under optical microscopy. Weld nugget (fusion zone) sizes were measured on the weld cross section parallel to the rolling direction. 4% Nital etching reagent was used to reveal the fusion line boundary. Microhardness test was used to determine the minimum hardness in HAZ, using 100g load on a Bohler microhardness tester.

RESULTS AND DISCUSSION

Hardness Profile: Fig. 1 shows the macrostructure of dissimilar RSW of DP600 and low carbon steel indicating that there are three distinct microstructural zones:

- Weld nugget (WN) or fusion zone (FZ) which is melted during the welding process and is resolidified showing a cast structure. Macrostructure of the weld nugget consists of columnar grains.
- Heat affected zone (HAZ) which is not melted but undergoes microstructural changes.
- Base metal (BM)

Fig. 2 shows a typical hardness profile of the spot welds. Hardness of FZ is higher than that of the BM. This can be attributed to the formation of martensite in FZ. Martensite formation in FZ of dual phase steel RSWs is well documented in literatures [9, 10, 20].

A reduction in the hardness (softening) with respect to the BM was observed in the HAZ of DP780 and DP980 spot welds. HAZ softening during welding of DP steels has been reported in the literature [11-13].

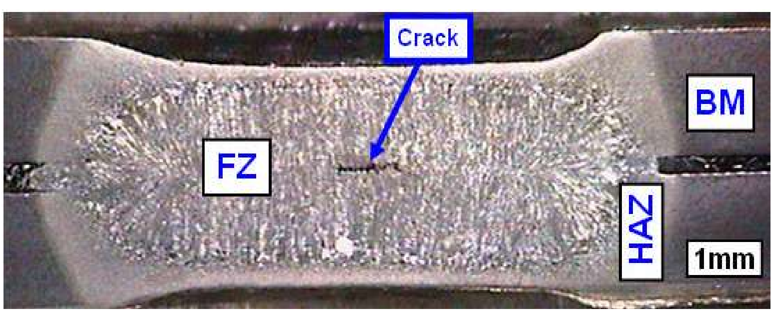

Fig. 1: Macrostructure of DP980 RSW

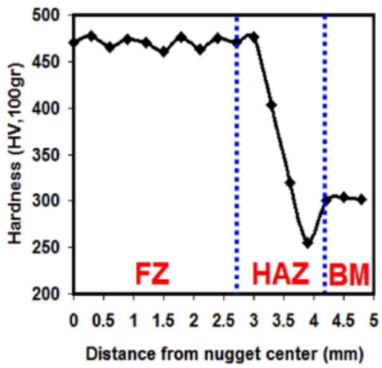

Fig. 2: A typical hardness profile for DP980 spot welds

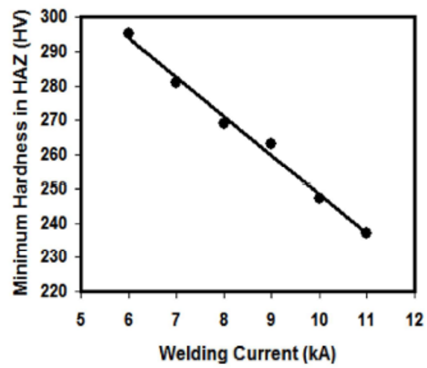

Fig. 3: Effect of welding current on the minimum hardness in the HAZ

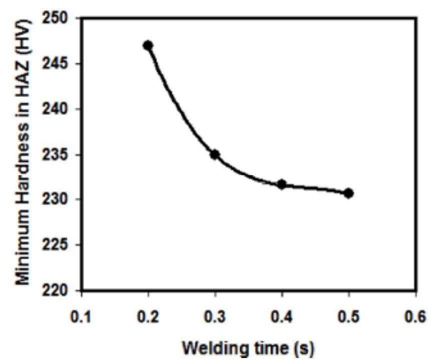

Fig. 4: Effect of welding time on the minimum hardness in the HAZ

The location of HAZ softening corresponds to the sub-critical HAZ (i.e. the region in HAZ which experiences temperatures below Ac1 critical temperature). It is well documented that this phenomena is due to the tempering of the pre-existing martensite in the sub-critical areas of the HAZ [16]. Recently, Baltazar *et al*. [21] studied the HAZ softening of DP980 RSW via nano-indentation hardness test. They concluded that at the tempered region, the ferritic matrix presented a slight hardness reduction (probably due to the possible reduction in the dislocation density) while the tempered martensite seemed to have a major contribution to the measured softening at micro-scale.

The degree of the HAZ softening depends on the martensite volume fraction of the BM. Xia *et al*. [16] studied the HAZ softening behavior of DP steels during laser welding. They found that the amount of HAZ softening is directly proportional to the martensite volume fraction. Higher DP grades exhibit greater potential for HAZ softening due to larger volume fraction of martensite which experiences post-weld tempering. It should be noted that the degree of HAZ softening is also depends on the welding process and heat input rate. The higher the heat input, the higher the degree of HAZ softening is. For example, HAZ softening of DP600 during RSW is not reported in the literature, due to rapid thermal cycle of RSW and short dwell time at the peak temperatures, as well as its martensite low volume fraction; while, some softening of HAZ-DP600 is reported during arc welding [22] and laser welding [16].

Effect of Welding Parameters on the HAZ Softening: To study the effect of welding parameters on the HAZ softening, welding was carried out in various welding condition and the minimum hardness in the HAZ was determined.

Fig. 3 shows the effect of welding current on the minimum hardness in the HAZ. As can be seen, the loss of hardness value in the HAZ becomes more severe as the welding current increases. For example, for DP980 RSWs, minimum hardness in HAZ varied from 295 to 238 HV (i.e. about 20% increase in softening) by increasing welding current from 6 to 11kA. As the welding current increases, the retention time above effective martensite tempering increases and this leads to more HAZ softening.

Fig. 4 shows the effect of welding time on the minimum HAZ hardness. This can be related to the higher heat input and the higher retention time above effective martensite tempering. However, as can be seen increasing welding time beyond 0.2 s has not significant influence on the HAZ softening. This indicates that the tempering process in the HAZ is stabilized after 0.2 s.

Fig. 5 shows the effect of electrode force on the minimum hardness in HAZ. As can be seen increasing electrode force increases the minimum hardness in the HAZ.

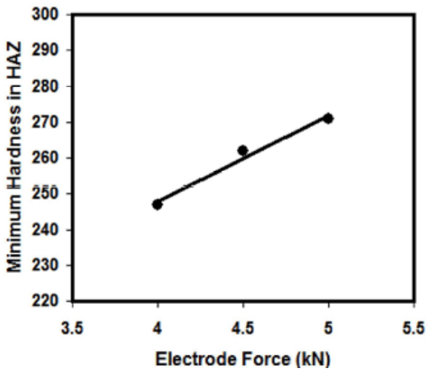

Fig. 5: Effect of welding force on the minimum hardness in the HAZ

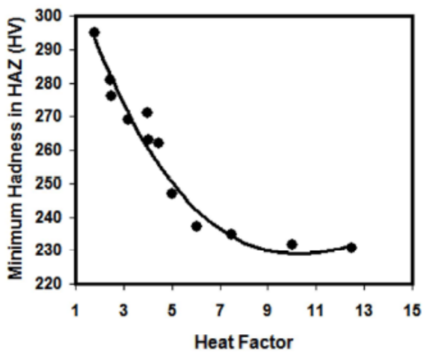

Fig. 6: Effect of heat factor on the minimum hardness in the HAZ

The amount of heat generated at the sheet-to-sheet interface during the spot welding process is mainly responsible for nugget formation and its strength. Generated heat during resistance spot welding can be expressed as follows:

$$Q=RI_w^2\, t_w \tag{1}$$

Where, Q, R, I_w and t_w are generated heat, electrical resistance, welding current and welding time, respectively. Therefore, the three main parameters affecting the weld nugget growth are welding current, welding time and electrical resistance. This heat varies directly with interface resistance, weld time and second power of welding current. Again this contact (interface) resistance varies in a complex manner and is influenced by the electrode force, surface conditions of the sheets used and also with the geometry of the electrode tip.

Increasing welding current and welding time increases heat generation. Static electrical resistance (i.e. contact resistance) is mainly governed by the electrode force which in turn controls the weld nugget formation. In a ductile material, as normal force is applied across the contact interface, the number of surface asperities supporting the applied load gradually increases due to their successive yielding. In other words, the true contact area will initially be a relatively small fraction of the macroscopic or apparent contact area. The true contact area will increase with the application of load and, in the limit, will approach the apparent contact area. Therefore, increase in electrode force, decreases the electric resistance and thus reduces the generated heat at the sheet/sheet interface.

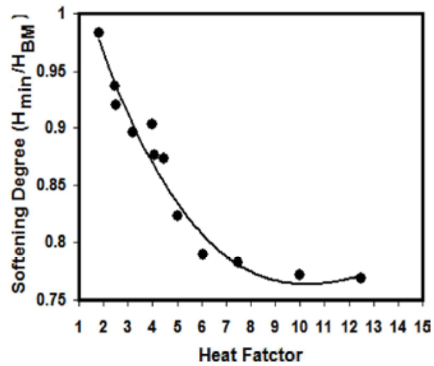

Fig. 7: Effect of heat factor on the softening degree

According to the above discussion, a parameter, the so called "Heat Factor", can be defined as follows:

$$\text{Heat Factor} = \frac{I_W^2\, t_W}{F_e} \tag{2}$$

Where, F_e is the electrode force.

Fig. 6 shows the effect of heat factor on the minimum hardness in HAZ. As can be seen, increasing heat factor decreases the minimum hardness of the HAZ. However, as can be seen, increasing heat factor beyond 6, has not significant effect on the minimum HAZ hardness. Fig.7 shows the effect of heat factor on the HAZ softening degree. HAZ softening degree is defined as the minimum HAZ hardness to BM hardness. As can be seen the minimum HAZ hardness varies from 0.98 to roughly 0.77.

As mentioned, the HAZ softening is an important factor is determining mechanical properties of the spot welds. Generally, HAZ softening can improve RSW mechanical performance in terms of load bearing capacity and energy absorption capability via promoting PF mode at smaller FZ size. Therefore, it is important to control the degree of HAZ softening during resistance spot welding of DP steels.

CONCLUSION

Understanding the influence of RSW parameters on the HAZ softening is important to proper control of microstructure-properties relationship during spot welding of dual phase steels. The results of the present paper revealed how the minimum HAZ hardness is influenced by the main welding parameters, viz. welding current, welding time and electrode force.

- Increasing heat input caused by increasing welding current and welding time led to increasing the softening degree in the HAZ.
- Increasing electrode force can increase the initial sheet/sheet contact areas and therefore decreases the sheet/sheet interfacial electrical resistively, which in turn leads to reduction in the generated heat at sheet/sheet interface. Therefore, increasing electrode force decrease the HAZ softening.
- A factor, heat factor=I^2t/F defined to evaluate combining effects of welding parameters on the HAZ softening. It was shown that, increasing heat factor decreases the minimum hardness of the HAZ. However, increasing heat factor beyond 6, has not significant effect on the minimum HAZ hardness.

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