Materials and Design 54 (2014) 598–609

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Effect of boron content and welding current on the mechanical properties of electrical resistance spot welds in complex-phase steels

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ARTICLE INFO

Article history:
Received 31 May 2013
Accepted 28 August 2013
Available online 4 September 2013

Keywords:
Complex phase steel
Resistance spot welding
Boron content
Nugget diameter
Tensile-shear load

ABSTRACT

When complex phase steel where tensile strength is more than 1 GPa grade is joined by resistance spot welding (RSW) optimum boron (B) content should be chosen to satisfy weldability and mechanical properties. Therefore, in this study, the effect of the B content (0–40 ppm) on the tensile-shear strength of the RSW were investigated. As the resistivity of the base metal was independent on the B content it did not affect to nugget diameter. Regardless of the B content the specimens under $5t^{1/2}$ (t = sheet thickness) were fractured at interfacial failure mode. In the low welding current condition (lower than 6.4 kA), measured nugget diameters were smaller than calculated critical nugget diameter regardless of the amount of B addition so that fracture mode was interfacial failure. Pull out failure occurred at the softened zone which was boundary between the base metal and the heat affected zone. Tensile-shear load of the specimen failure at the pull-out mode was increased as the fractured diameter and hardness of the softened zone were increased. Shear load was only dependent on the fractured diameter. The equations to calculate the shear and tensile-shear load were suggested for the specimens fractured at interfacial and pull-out failure modes respectively. Correlation coefficients between measured and calculated values of shear and tensile-shear load were 0.98 and 0.97, respectively. Therefore, shear and tensile-shear load of advanced high strength steel joined by RSW could be predicted successfully using the suggested equation.

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1. Introduction

In order to improve fuel economy of an automobile, the weight of an auto body should be reduced. Lightweight and maintaining strength had trade-off relationship, so there should be much researches to find the optimum combination of them. Recently, due to the strengthened safety regulation for car passengers and pedestrians, installation of the safety device became compulsory. However, this resulted in the increase of weight of the auto body. Therefore, the development of advanced materials with high strength more than 1 GPa and high ductility is essential to overcome this problem.

Transformation induced plasticity (TRIP), complex phase (CP), and twinning-induced plasticity (TWIP) steels, etc. which had mixed microstructure with high strength and ductility were produced and make a great contribution to the weigh saving of automotive [1–3]. The CP steel consisted of the mixed microstructure of martensite, retained austenite, bainite and ferrite, and had high yield strength and good formability so that it was in the spotlight as the material for the auto body. However, the development and application of the CP steel was not sufficient yet [1,2].

On the other hand, in the normal steels boron (B) was known to suppress nucleation of ferrite by segregation in austenite grain boundaries and increase hardenability with the addition of ppm scale [4,5]. This element attracted interest again to secure high strength more than 1 GPa in advanced high strength steel (AHSS). The boron steel for hot-stamping (25 ppm addition of B) which showed the tensile strength of 1.5 GPa after hot stamping was reported in the literature [6].

To produce auto body parts as final product welding process is necessary, and resistance spot welding (RSW) and laser beam welding (LBW) were most widely used. Previous research for this was as follows. Since year 2000, many researches about microstructures and mechanical properties of the weld by RSW and LBW got accomplished in the DP and TRIP steels for automotive which were AHSS with 590–1180 MPa grade [7–14]. Especially, when DP780 and DP980 steels which had high volume fraction of martensite within base metal were joined by RSW softened zone occurred at the boundary of the base metal and HAZ [15–17], and

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0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.08.098

Nomenclature

TSL	tensile shear load (kN)
ND	measured nugget diameter (mm)
TSL_{PF}	tensile shear load in pull out failure (PF) mode (kN)
α	constant related to the stress distribution
FD_{SZ}	diameter of the fractured region in PF mode (mm)
t	thickness of base metal (mm)
σ_{SZ}	tensile strength of the softened zone (kN/mm^2)
σ_{BM}	tensile strength of the base metal (kN/mm^2)
Hv_{BM}	hardness of the base metal (Hv)
Hv_{SZ}	minimum hardness of the softened zone (Hv)
τ_N	shear strength of the weld nugget (kN/mm^2)
σ_N	tensile strength of the weld nugget (kN/mm^2)
SL_{PF}	shear load in interfacial failure (IF) mode (kN)
FD_N	diameter of the fractured region in IF mode (mm)
β	constant with the notch effect
Hv_N	hardness of the weld nugget (Hv)
$\sigma_{BM/W.Q}$	tensile strength of the base metal water quenching (kN/mm^2)
$Hv_{BM/W.Q}$	hardness of base metal water quenching (Hv)
$ND_{Cri.}$	critical nugget diameter to transit from IF to PF (mm)

fracture started at this zone so that the strength of the joint was decreased [18–20]. In addition, many researcher reported the correlation between microstructure/mechanical properties and softening phenomenon on the RSW of these AHSS [14,15,21,22]. Recently, Choi et al. [23] reported that solidification crack and void were formed within nugget in the weld of GA-DP780 and hot-stamped Al–Si coated B steels joined by RSW. These defects resulted in the interfacial failure and decreased the strength of the joint. Kim et al. [24] and Hu et al. [25] said that the softening phenomenon occurred at the boundary of base metal/HAZ in the laser weld of CP1180 and CP1000 steels respectively. However, discussions about that phenomenon were not provided sufficiently. Up to now, most of the researches focused on the effect of the process parameters on the microstructure and mechanical properties in the laser and spot welds of DP, TRIP and boron steels. However, in case of the CP steel, the effects of alloying element as well as those effects were hardly found in the literature.

On the other hand, Park et al. [26] investigated the effect of the B content on hardness of disk-laser weld in the CP steel and reported that the hardness of base metal and softened zone was increased due to the increase of the martensite volume fraction. This study meant that the B content had an influence on the microstructure and mechanical properties of the resistance spot welds as well as the base metal in the CP steel. However, there was no systematic research about the topic.

In this study, in order to obtain optimum B content to satisfy the requirement for weldability and mechanical properties of the resistance spot welds in the CP steel where the tensile strength of base metal was more than 1 GPa, the effects of the B content (0–40 ppm) and welding current on the tensile-shear load of the resistance spot welds were examined. Correlations between the load, and failure mode and microstructure were also investigated.

2. Experimental procedure

The materials used in this study were 1.2 mm thick cold rolled complex steel (CP) sheets containing different amounts of boron (B). Materials used in this study were not fabricated in the lab but supplied by domestic steel manufacturer. Table 1 lists the chemical composition and tensile properties of the base metal. In the given composition range (0–40 ppm B) the interval of the composition change was 10 ppm from 0B to 10B steels and 15 ppm from 10B to 40B steels. And then, the effect of B content on the mechanical properties was investigated.

Table 1
Chemical compositions and tensile properties of investigated base metals.

No.	wt.%				ppm			Tensile properties		
	C	Si	Mn	Cr	P	S	B	TS (MPa)	YS (MPa)	EL (%)
0B	0.07	0.1	2.1	1.0	200	30	0	840	390	21
10B							10	930	470	15
25B							25	1020	530	11
40B							40	1110	537	9

Spot welding was performed using a PLC-controlled, 120-kVA AC pedestal-type resistance spot welding machine. Welding was conducted using a 45-deg truncated cone RWMA Class 2 electrode with a 6-mm face diameter. The welding currents were varied from 5 to 9 kA, and the welding time, electrode pressure and holding time were fixed to 17 cycles, 4 kN and 40 cycles, respectively. In the present study, the welding parameters were adjusted to avoid expulsion. Tensile-shear tests were performed to evaluate the mechanical performance and failure mode of the spot welds. The samples were prepared due to ANSI/AWS/SAE D8.9M:97 [27].

Fig. 1 shows the test sample dimensions for the tensile-shear tests [28]. The mechanical tests were performed at a cross-head of 5 mm/min with an Instron® universal testing machine. The tensile-shear load (measured as the peak point in the load–displacement curve) was extracted from the load–displacement curve. The data points for the tensile-shear load are the average of three measurements.

The failure modes of the spot welds specimens were determined by an examination of the fractured samples. Specimens for optical and scanning electron microscopy (SEM) were prepared using standard metallographic practices. Polished specimens were etched with 2% Nital solution and then used to observe the microstructures using optical microscope and SEM. EBSD analysis was carried out using the specimens which were taken from the joint, ground using general SiC paper and polished by 0.04–0.05 μm colloidal silica for 20 min. Vickers mirco-hardness test was performed across the spot welds. A load of 0.2 kgf and a dwell time of 10 s were used during testing.

3. Results and discussion

3.1. Effect of B content and welding current on tensile strength

Generally, the most important factor for the tensile-shear load (TSL) and failure mode is the nugget diameter [11,18,29]. The

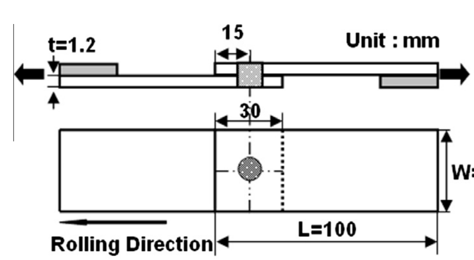

Fig. 1. Tensile-shear test sample dimension (JIS Z 3136 [28]).

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