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Uni- and bi-axial deformation behavior of laser welded advanced high strength steel sheets

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ABSTRACT

Bead-on-plate butt joints of 2.5 mm hot rolled DP600/DP600 and 1.2 mm cold rolled TRIP700/TRIP700 steel sheets were performed using 6 kW CO_2 laser beam welding. The welding speed ranged from 1.5 to 3.0 and from 2.1 to 3.9 m/min in DP/DP and TRIP/TRIP steel weldments respectively. A top surface helium gas was used as a shielding gas at a flow rate of 20 l/min. Metallographic examinations and transverse tensile testing (DIN EN 895: 1995) were carried out to characterize the weldments. The formability of base metals and weldments were investigated by standard Erichsen test (DIN EN ISO 20482). It was found that the uniaxial plastic behavior of both DP600 and TRIP700 base metals was in agreement with Swift and modified Mecking–Kocks models respectively. In a perpendicular tensile test to the weld line, all specimens were fractured at the base metal however the strengths were somewhat higher than those of base metal. There was a significant reduction in formability caused by welding of both DP/DP and TRIP/TRIP steel weldments and the formability has been improved with the increase of the welding speed.

1. Introduction

Advanced high strength steels (AHSS), such as dual phase (DP) and transformation-induced plasticity (TRIP), are increasingly used to meet the stringent requirements imposed by the automotive industry in terms of safety, reliability and reduction in gauge for energy saving, as showed by Rizzi et al. (2009). The strength level in DP steels is related to the amount of martensite in the microstructure, appointed out by Castro et al. (2009) while the enhanced formability in TRIP steels comes from the transformation of retained austenite (ductile, high temperature phase of iron) to martensite (tough, non-equilibrium phase) during plastic deformation.

Among other welding methods of AHSS, laser beam welding and mash seam welding have received much more attention. Laser welding is fast, precise, reliable and able to join a wide variety of materials, both varying in thickness and type. Kang et al. (2007) evaluated the microstructures, tensile properties and formability of neodymium-doped yttrium aluminum garnet (Nd: YAG) laser welding of 600 MPa grade TRIP and DP steels. They concluded that the mechanical properties of the weldments are strongly affected by changing of the welding speed. The characteristics of CO_2 laser welding of TRIP 800 MPa steel under different shielding gases such as helium (He), argon (Ar) and He–Ar mixtures are studied by Han et al. (2005). They showed that the porosity fraction of the bead produced with Ar is larger than that of the bead produced with He.

Both DP and TRIP steels typically exhibit good formability due to their unique microstructural makeup but the changes in local material properties caused by welding tend to negatively affect the formability of welded blanks. Xia et al. (2008a) studied the effects of heat input and martensite fraction on heat affected zone (HAZ) softening in laser welded DP steels. They appointed out that the total extent of HAZ softening at large heat input is proportional to the martensite content of the DP steels. Sreenivasan et al. (2008) indicated that the HAZ softening, frequently occurs as a result of martensite tempering, has a significant effect on the formability of high strength steels where the softened zone is characterized by lower hardness and strength than the base metal. Concurrently, in the fusion zone, hardening readily occurs especially with low heat input welding processes. Generally, these effects result in deterioration of the overall mechanical performance of weldments.

The forming behavior of welded sheets was influenced by many factors, such as material property changes in the fusion zone (FZ) and HAZ. In the biaxial stretch forming, two distinct failure modes have been observed. If the thickness and strength ratios of the two sheets are such that weld line movement is limited during forming, failure tends to initiate in the hardened weld metal and propagate perpendicularly into the base metal. On the other hand, if there is significant weld line movement due to strength or thickness mismatch, the failure tends to occur parallel to the weld in the weaker of the two base metals when the ultimate tensile stress is exceeded.

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Table 1
Chemical compositions (wt%) and C-equivalents of DP and TRIP steel.

	C	Mn	Al	Si	P	S	Cr	Mo	Ni
DP600	0.057	0.860	0.029	0.0958	0.0260	<0.001	0.4180	0.0056	0.0390
TRIP700	0.182	1.560	1.040	0.0706	0.0706	<0.001	0.0155	<0.005	0.0289
		CEN (Yorioka)			CE (IIW)				
DP600		0.18			0.29				
TRIP700		0.45			0.45				

However, a third failure mode, namely failure at the HAZ, has been recently observed in weldments of high strength steels due to the softened zone formation. Xia et al. (2008c) studied the failure of laser welded DP steel sheets in formability testing. They indicated that the HAZ in DP980 weldments completely dominated the fracture pattern where it was the vulnerable region in which the failure always initiated. During the welding of DP980 and DP800 steels, the strain and fracture were localized in the softened HAZ, as showed by Panda et al. (2009). Cheng et al. (2007) and Chan et al. (2003) investigated the formability and tensile properties of different thickness tailor-welded blanks. They stated that the failure generally occurs in the thinner base metal of the welded blanks and specific considerations should be taken into account during the welding process to obtain optimum tensile properties and formability. The details of failure initiation and propagation on a microscale level during biaxial testing are still unknown.

This research work aims to investigate and evaluate the uni- and bi-axial behaviors of the laser welded DP600/DP600 and TRIP700/TRIP700 steel sheets.

2. Experimental work

2.1. Material selection

2.5 mm hot rolled DP600 and 1.2 mm cold rolled TRIP700 steel sheets were used in this study. The chemical compositions and carbon equivalents of the investigated steels are summarized in Table 1. The microstructures of tested steel sheets were characterized using optical microscopy (OM) and scanning electron microscopy (SEM). A quantitative measurement of retained austenite present in the TRIP steel was carried out by X-ray diffraction measurements using Co Kα radiation.

2.2. Laser beam welding

Bead-on-plate DP/DP and TRIP/TRIP steel sheet weldments were produced with 6 kW CO_2 beam laser. The applied powers were 3.5 and 4.5 kW for DP/DP and TRIP/TRIP steel weldments respectively. The welding speed ranged from 1.5 to 3.0 and from 2.1 to 3.9 m/min in DP/DP and TRIP/TRIP steel weldments respectively. The focal position was 0 mm in all welding attempts. Butt joint configuration with the weld line oriented parallel to the rolling direction and full penetration were obtained in all weldments. Helium was employed as a shielding gas from the top surface at a flow rate of 20×10^{-3} m^3/min (20 l/min).

2.3. Mechanical characterization of base metals and weldments

Transverse samples were cut from representative welds for metallographic observations, microhardness measurements and tensile properties evaluations. The characteristics of fusion and heat affected zone microstructures were carried out by the optical microscopy. Vickers microhardness testing using DIN EN 1043-2: 1996 (HV 0.1) was conducted on nital etched samples with load holding time of 10 s and measured by 0.1 mm intervals on a virtual line located in the half of the thickness of the weldments.

Room temperature uniaxial tensile testing was used to evaluate the tensile properties of the base metals using DIN EN 10002-1: 2001. To study the effect of anisotropy, the specimens were tested along three directions with tensile axis being parallel (0°), diagonal (45°) and perpendicular (90°) to the rolling direction of the sheets. Transverse samples were cut from representative welds for tensile properties evaluations of the weldments using DIN EN 895: 1995. The crosshead speed was constant in all tensile testing and equal to 10 mm/min. The standard tensile properties (yield stress, ultimate tensile strength and elongation) were determined. The true stress/true strain curves are sketched depending on the experimental engineering stress/engineering strain data using the following relationships:

$$\sigma = s(1+e) \tag{1}$$

$$\varepsilon = \ln(1+e) \tag{2}$$

where s, e, σ and ε are engineering stress, engineering strain, true stress and true strain respectively.

The plastic behavior of both base metals was examined by Hollomon, Swift, Ludwick and modified Mecking–Kocks models (El-Magd, 2004; Kleemola and Nieminen, 1974).

$$\sigma = k\varepsilon_p^{n_0} \quad \text{Hollomon} \tag{3}$$

$$\sigma = \sigma_0 + k\varepsilon_p^{n_1} \quad \text{Ludwick} \tag{4}$$

$$\sigma = k(\varepsilon_0 + \varepsilon_p)^{n_2} \quad \text{Swift} \tag{5}$$

$$\sigma = \sigma_0 + c_1\varepsilon_p + c_2[1 - \exp(c_3\varepsilon_p)] \quad \text{modified Mecking–Kocks} \tag{6}$$

where σ is the true stress, ε is the true strain, k is the strength coefficient, n_0, n_1 and n_2 are the strain hardening exponents for Hollomon, Ludwick and Swift equations respectively and c_1, c_2 and c_3 are constants.

The formability of both base metals and weldments was evaluated using the Erichsen test according to DIN EN ISO 20482. The experimental set-up is shown in Fig. 1. The welded specimens were carefully placed to locate the weld line at the centre of the dome punch. A 20 mm diameter hemispherical punch was used with a velocity of 10 mm/min. Draw-in of the specimens was resisted by 200 kN as sheet holder force to assure a pure stretching condition. The resulting stress state was nearly biaxial, with strain in both transverse (perpendicular) and longitudinal (parallel) directions with respect to the weld line. Each coupon was stretched to failure and the limiting dome height was taken at the peak punch load. To minimize friction between the punch and sheet, specimens were cleaned and lightly coated with graphitized grease. The dies were thoroughly cleaned before each test. The welded samples were positioned with the bottom of the weld facing out so that the punch made contact with the front side.