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Fatigue properties and failure characterization of spot welded high strength steel sheet

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Abstract

Fatigue properties and failure characterization of high strength spot welded steels, such as DP600 GI, TRIP600-bare and HSLA340Y GI, have been conducted. Tensile shear and coach peel samples have been used in this investigation. HSLA340Y GI samples were used as the baseline material for comparison. Microhardness was measured to study the hardness change across the weld nugget. Under low load and high cycles situation all the materials show very similar fatigue strength. Crack initiation and propagation during the fatigue loading history has been experimentally determined and discussed. Microhardness tests show that DP600 GI samples have the highest hardness, about 420 HV in weld nugget and 250 HV in base metal, followed by TRIP600-bare, about 400 HV in weld nugget and 220 HV in base metal, and HSLA340Y GI, about 320 HV in weld nugget and 160 HV in base metal. It was also found that both DP600 GI and HSLA340Y GI display softening during high load and low cycles fatigue tests with HSLA showing more prominent softening behavior.

Keywords: Fatigue properties; Dual phase steel; Transformation induced plasticity steel; High strength low alloy steel

1. Introduction

With increasing demands for higher fuel efficiency in automobiles, new structural materials are being considered among other strategies. New materials are being evaluated for their light-weight or their superior strength, with the ultimate goal of reducing the weight of the vehicle, which will result in lower fuel consumption. In this regard, aluminum alloys and advanced high strength steels (AHSS) are being investigated for substituting currently used low-carbon steels and high strength low alloy (HSLA) steels. Although aluminum alloys, such as 6111 and 5754, have only one-third the density of steel, their widespread use in automobiles has been limited because of its higher costs and difficulties in manufacturing, such as forming and welding [1].

AHSS is obtained by controlled cooling from an intercritical annealing process followed by lower-temperature austenite transformation [2,3]. Depending on different alloy elements and cooling process, AHSS has different finial microstructures. Dual phase (DP) steel consists of ferrite and martensite, and the mechanical properties are controlled by the volume fraction of martensite and ferrite grain size. Transformation induced plasticity steel (TRIP) consists of ferrite, bainite and austenite. Retained austenite plays a very important role in the TRIP steel's mechanical performance. When TRIP steel is subjected to plastic deformation in manufacturing or in service, the retained austenite can transform to martensite accompanied by a large elongation. This is the so called transformation-induced plasticity (TRIP) effect. AHSS, such as dual-phase steel DP600 GI and transformation induced plasticity steel TRIP600-bare have tensile strengths over 600 MPa, compared to conventional high strength steels within the range of 400–440 MPa, though they have similar yield strengths and are good candidates for making lighter-weight vehicles. These advanced steels typically exhibit higher yield

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strength, low yield to tensile strength ratio, good formability, high work hardening rate, and high strain energy absorption capabilities. As a result some of the sections of an automobile such as doors, and front and rear longitudinal rails, can be made of a thinner section that reduces the weight of the vehicle while absorbing significant deformation energy due to the high work hardening rate and ductility. Thus, thinner AHSS sheets, which decrease the weight of an automobile, can be used without loosing any strength, and having a similar or higher level of crash energy absorption.

The materials mentioned above can be joined by a variety of methods, but spot welding still remains the primary joining method in automobile body manufacturing till today. A typical vehicle could contain more than 3000 spot welds [2]. AHSS steels, as any other material used in automobiles, can undergo significant fatigue damage, which is related to the reduction in sheet thickness [4–7]. Thus, it is imperative to investigate the fatigue behavior of spot welded joints in thin section AHSS for achieving a safe and reliable design.

The purpose of this study is to experimentally investigate the weld fatigue properties of AHSS steels (DP600 GI and TRIP600) and compare with the baseline material HSLA340Y GI for both coach peel and tensile shear type specimens under tension–tension sinusoidal loads. The fatigue crack initiation and propagation has been studied and the failure mechanisms have been discussed.

2. Experimental procedure

2.1. Materials and specimen

The chemical composition and mechanical properties of AHSS steels and HSLA steel are shown in Table 1 and Table 2, respectively [2].

Specimens used for fatigue tests were tensile shear type and coach peel type, as shown in Fig. 1. Samples were supplied by Auto Steel Partnership. The thickness is 1.53 mm for DP600 GI, 1.64 mm for TRIP600, and 1.78 mm for HSLA340Y GI. Tensile shear type specimens have a length of 217 mm and width of 38 mm. Coach peel specimens have a length of 155 mm and width of 38 mm. In tensile shear specimens suitable tabs were glued to the specimen ends to reduce bending deformation at the joint during the fatigue tests. The average diameter of spot weld nugget was measured to be approximately 7.0 mm for all samples.

2.2. Fatigue test procedure

An Instron universal servohydraulic testing machine with a 8800 Plus controller was used to conduct load-controlled tension–tension fatigue test. The samples were subject to various sinusoidal load with a load-ratio $R = 0.1$ or $R = 0.3$, at a frequency of 5 Hz for coach peel samples and 10 Hz for tensile shear samples. For the case of $R = 0.3$, a constant load amplitude was set when compared with that

Table 1
Nominal chemical composition of AHSS steels and HSLA steel (wt%)

Steel	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Al	V	Cb
DP600 GI	0.081	1.760	0.017	0.006	0.013	0.040	0.02	0.19	0.180	0.048	0.002	0.004
TRIP600	0.101	1.470	0.002	0.001	1.536	0.016	0.02	0.05	0.010	0.027	0.005	0.005
HSLA340Y GI	0.053	0.620	0.008	0.005	0.214	0.052	0.02	0.01	0.000	0.039	0.001	0.016

Table 2
Nominal mechanical properties of AHSS steels and HSLA steel

Steel	0.2% offset yield strength (MPa)	Ultimate tensile stress (MPa)	Uniform elongation (%)	Total elongation (%)
DP600 GI	432.6	671.4	13.6	22.1
TRIP600	420.9	672.8	20.6	29.3
HSLA340Y GI	369.2	448.5	15.9	31.7

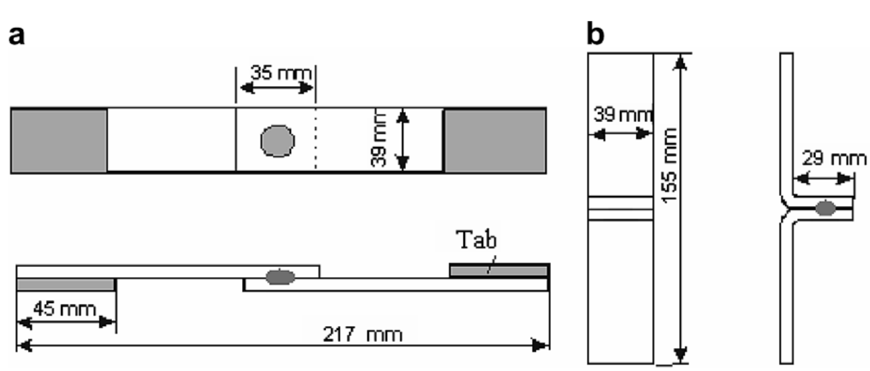

Fig. 1. (a) Tensile shear type and (b) coach peel type fatigue specimens.

of $R = 0.1$. Thus, the maximum, minimum and mean load at $R = 0.3$ were higher from that of $R = 0.1$ case, but the amplitude was the same. The maximum dynamic load used was typically about 60% of the maximum load obtained during a quasi-static tensile test. During the fatigue test, the maximum load, minimum load, maximum and minimum cross head displacement, and the frequency were monitored by using the Instron Wave Maker Data Acquisition software and 8800 Plus digital controller.

For microstructure and fracture morphology observation of the failed sample, they were cut along the center of the spot nugget in the direction of the length of sample. The cross section of the cut samples was polished and then etched. The etchant used was 3% Nital (3 mL HNO_3 and 97 mL alcohol).

Microhardness tests were conducted on the surface of the sectioned and polished samples used for microstructure observation. A Micromet II microhardness tester was used to conduct Vickers hardness tests with a load of 300 g.

3. Results and discussion

3.1. Quasi-static tension properties

Quasi-static tension tests were conducted with tensile shear and coach peel samples for each of the materials. Fig. 2 shows typical load vs. displacement curves for various spot-welded samples and the average maximum load sustained by these samples are listed in Table 3. It can be seen from Table 3 and Fig. 2 that TRIP600 tensile shear samples have the highest strength among three types of

Table 3
Maximum load carrying capacity of tensile shear and coach peel samples

Material	Tensile shear samples (kN)	Coach peel samples (kN)
DP600 GI	20.95	3.64
TRIP600	23.58	3.29
HSLA340Y GI	17.82	4.84

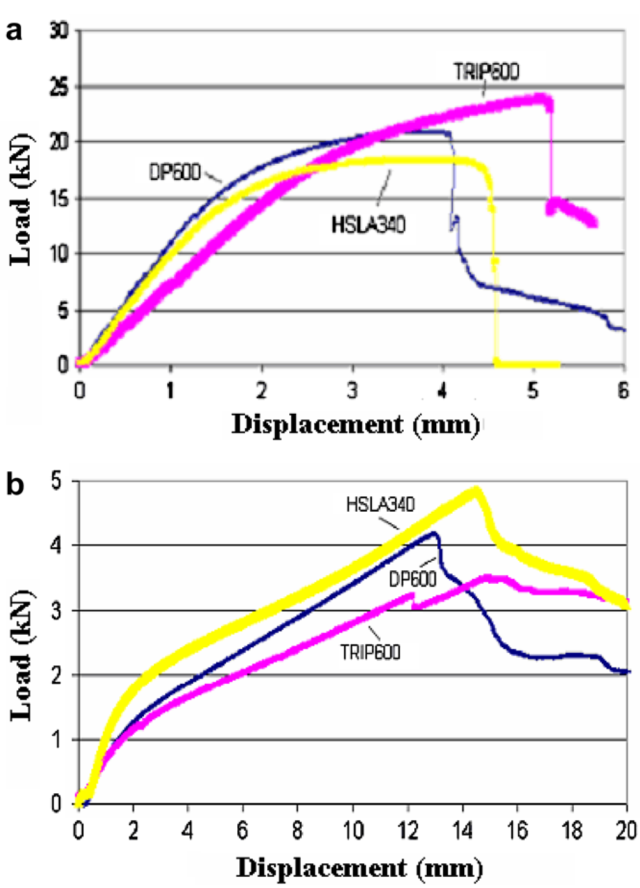

Fig. 2. Typical load vs. displacement plots under quasi-static loading of: (a) tensile shear and (b) coach peel samples.

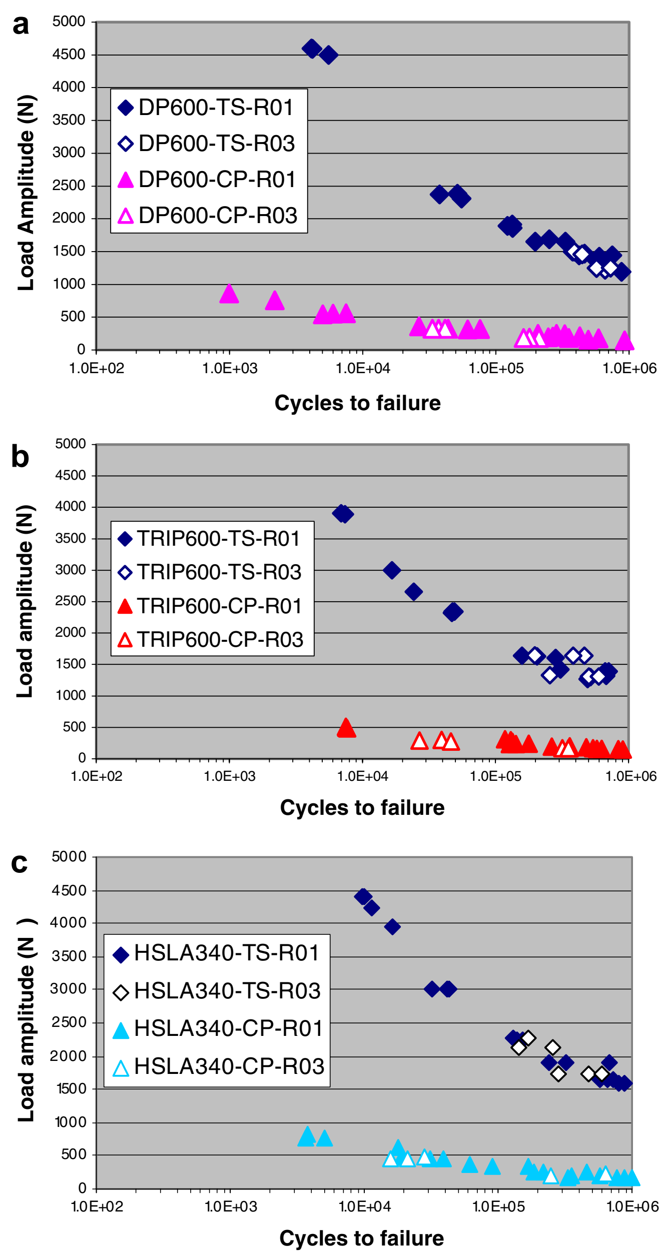

Fig. 3. Load amplitude vs. cycles to failure curves for: (a) DP600 GI, (b) TRIP600 and (c) HSLA340Y GI (TS, tensile shear; CP, coach peel, R01, R-ratio of 0.1; and R03, R-ratio of 0.3).

materials (32% higher than that of HSLA340Y GI sample and 13% higher than that of DP600 GI). For coach peel samples, however, the situation is just the opposite. HSLA340Y GI samples display the highest load carrying capacity and TRIP600 has the lowest maximum load.

3.2. Fatigue properties

The fatigue life curves of the three materials under consideration are shown in Fig. 3. It can be seen from Fig. 3 that the fatigue strength for low cycles (higher load) of DP600 GI samples is very similar to that of TRIP600 samples, and both of them have lower fatigue strength than that of HSLA340Y GI samples for both tensile shear and coach peel specimens. However, this difference is mainly due to the higher sheet thickness of HSLA specimens. For high cycles (lower load), the fatigue strength is approximately the same for all three types of materials and for both tensile shear and coach peel samples. The slightly higher fatigue strength of HSLA specimens, as seen in Figs. 3 and 4, is again due to the somewhat higher sheet thickness of HSLA specimens. For tensile shear samples, the fatigue strength for infinite life of DP600 GI and TRIP600 spot-welded joint is about 6–8% of the static joint strength. For coach peel samples, the above value is about 4%. Thus a high strength of base materials does not necessarily mean high fatigue strength of spot welded joint. These results agree with previous studies that the spot weld fatigue performance is independent of base materials strength at low load and high cycles [9,10]. The fatigue strength depends on the nature of the loading on the spot weld and the stress concentration factor of the circumferential notch around the weld.

3.3. Microstructure and fatigue crack characterization

3.3.1. Tensile shear samples

Microstructures and fatigue crack surface morphologies are shown in Figs. 5–7. Fig. 5 and Fig. 6 show the microstructure and fatigue crack path in DP600 GI and TRIP600 spot welded joints, respectively. The microstructures of DP600 GI and TRIP600 spot welds that were subjected to fatigue loading do not show any special characteristics under optical microscopy at low magnification, compared to an ordinary spot weld joint not subjected to fatigue loads. Coarse column dendritic crystals in the spot nugget are surrounded by about 0.7 mm thick heat affected zone (HAZ) areas for all three materials.

It has been observed that at high load and low cycles, fatigue crack in a tensile shear sample initiated outside the weld nugget for HSLA350 while in DP600 and TRIP 600 initiated close to the weld nugget and then propagates along the workpiece interface for a short distance (from HAZ of spot nugget to edge of nugget, about 0.8 mm), and then propagates perpendicular to the workpiece interface (that is out of the plane of the sheet) to complete fracture, as shown in Fig. 5b. For the case of low load and high cycles, the crack directly propagates perpendicular to the workpiece interface from the HAZ area of spot nugget, as shown in Fig. 5c.

Unlike DP600 GI spot weld, it was found that a "tongue" formed between the two workpieces of TRIP600 tensile shear samples around the spot nugget, which is shown in Fig. 6a. This tongue is usually the location for initiation of a fatigue crack under both high cycle and low cycle conditions, as shown in Figs. 6b and c. This could be the reason for the low fatigue strength of TRIP600 spot welded joints even though they have a high quasi-static tensile strength.

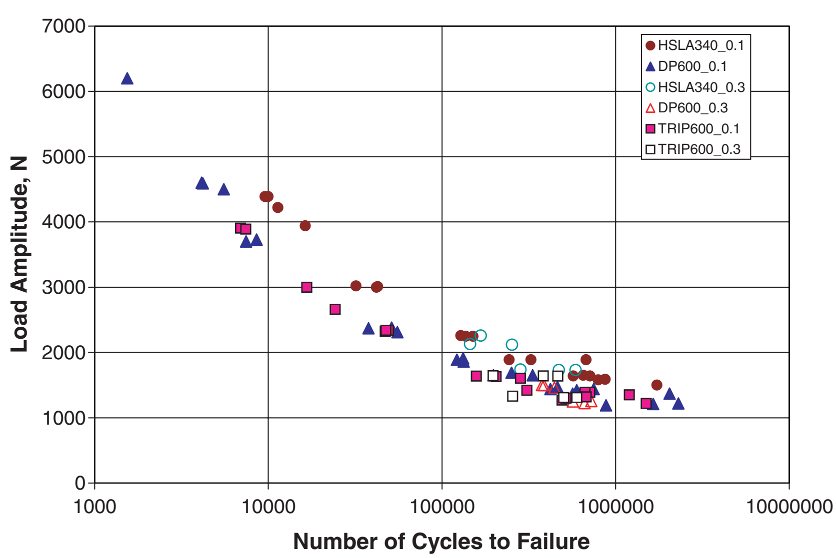

Fig. 4. Load amplitude vs. cycles to failure curves for: (a) DP600 GI, (b) TRIP600 and (c) HSLA340Y GI tensile shear type specimens (extension_0.1 represents a R-ratio of 0.1, _0.3 a R-ratio of 0.3).