

Influence of Geometric Parameters and Their Variability on Fatigue Resistance of Spot-Weld Joints

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ABSTRACT

Spot welding is the primary method of joining sheet metal for body and structural applications in the ground vehicle industry. A typical automobile may contain over 5000 spot welds. The fatigue failure of spot welded joints results in the degradation of both structural and Noise, Vibration, and Harshness (NVH) performance. Therefore, designers need reliable information about the total fatigue life of spot welded joints early on in the design phase.

Currently, automotive structures are employing ever increasing amounts of Advanced High Strength Steels (AHSS) including dual-phase steels. As a result, automotive designers require fatigue strength information on AHSS spot welds. The Auto/Steel Partnership (A/SP) has conducted fatigue tests with lap shear and coach peel specimens made of AHSS, HSLA and low carbon steels. Overall, the test data showed good correlation with the applied load range for all of the materials, regardless of base material strength. However, some scatter was observed in fatigue test data, especially in the data obtained from coach peel testing. This scatter may have resulted from several sources.

In order to understand the sources of scatter, the effect of geometric variations, material microstructure, and mechanical properties on fatigue life is investigated. Specifically, the variability in nominal values of spot weld diameter, specimen geometry including

specimen thickness, width, etc., and hardness values obtained in the HAZ and fusion zone are examined. The results of this study shed light on the importance of geometric parameters, such as specimen thickness and weld nugget diameter, and their large impact on the fatigue strength variability.

Keywords: Spot weld, Advanced High Strength Steels (AHSS), Fatigue strength, Automotive Sheet Steels

INTRODUCTION

The desire to reduce the emission of greenhouse gases from gasoline-powered automobiles, the need to meet tough safety standards, and the demand for more durable vehicles have resulted in the increased application of advanced high-strength steel (AHSS) in automotive body structures. The implications of the increased use of AHSS in body panels on the durability of welded joints needs to be examined. A typical uni-body structure contains more than 5000 spot welds to fasten panels and components together. The majority of spot welds generally carry primarily shear loads, but a number may experience significant peel loads (load normal to the spot weld faying surface) under certain loading conditions [1]. This multiaxial stress state combined with the spot weld's geometry causes stress concentrations that often result in fatigue crack initiation. The presence of fatigue cracks, possibly even a separated joint, degrades structural and NVH performance of the vehicle. Therefore, understanding the factors that affect

spot weld fatigue strength is crucial to vehicle structural design.

The Auto/Steel Partnership (A/SP) Sheet Steel Fatigue Committee conducted over 600 spot weld fatigue tests on a wide range of AHSS (DP600, DP800, DP980, TRIP600, TRIP800, RA830, hot-stamped boron steel, and MS1300), mild steels (IF, CQSK and DQSK), and a traditional high strength low alloy (HSLA340), and published a knowledge base of spot welded joints for use in vehicle structure design and durability [2]. Mild steels and traditional high strength steels were included in the study to form a basis of comparison with AHSS. In that the fatigue performance of the spot welded materials was essentially the same regardless of base material strength, the results of the A/SP study was very consistent with numerous previously published papers on spot welded joints (of mild steels and conventional high strength steels) [3-12].

This study investigates the sources of the scatter in the A/SP Sheet Steel Fatigue Committee's test results in two ways. Firstly, fatigue strengths of each steel grade are correlated to geometric factors (including sheet thickness, nugget size, coupon width, and distance from weld center to the grips) in order to understand the sources of scatter within each steel grade. Secondly, all fatigue results are then correlated to the same geometric factors in order to investigate the sources of scatter betwixt steel grades. Hardness values for the

steels under consideration were also correlated to fatigue life. Figure 1 shows the degree of scatter within each steel grade and amongst all steel grades tested. Please note that the DP 600 (0.93 mm-thick) material constitutes a separate dataset because of its substantially different thickness – the bulk of the materials were targeted to be 1.6 mm in thickness. The thicknesses listed in Figure 1 are nominal values, which differ slightly from the measured values.

MATERIALS, SPECIMEN GEOMETRY AND FATIGUE TESTING

This study examined failed specimens constructed of mild steel (Interstitial Free (IF-GI), Draw Quality Special Killed (DQSK-GI)), High Strength Low Alloy (HSLA340-GI), and AHSS steels including Dual Phase (DP600-GI and DP800-GA) TRAnsformation Induced Plasticity (TRIP600-Bare), Recovery Annealed (RA830-GI), MartenSitic (MS1300-Bare) and hot-stamped boron steel. Please note that a number of different surface conditions were present in the study including bare, galvanized (GI), and galvanneal (GA) coatings. The chemical compositions of the sheet steels studied are shown in Table 1. The team believed the DQSK used in this study was closer in composition to a titanium-stabilized IF steel. Thus, tests were conducted on a typical CQSK grade steel.

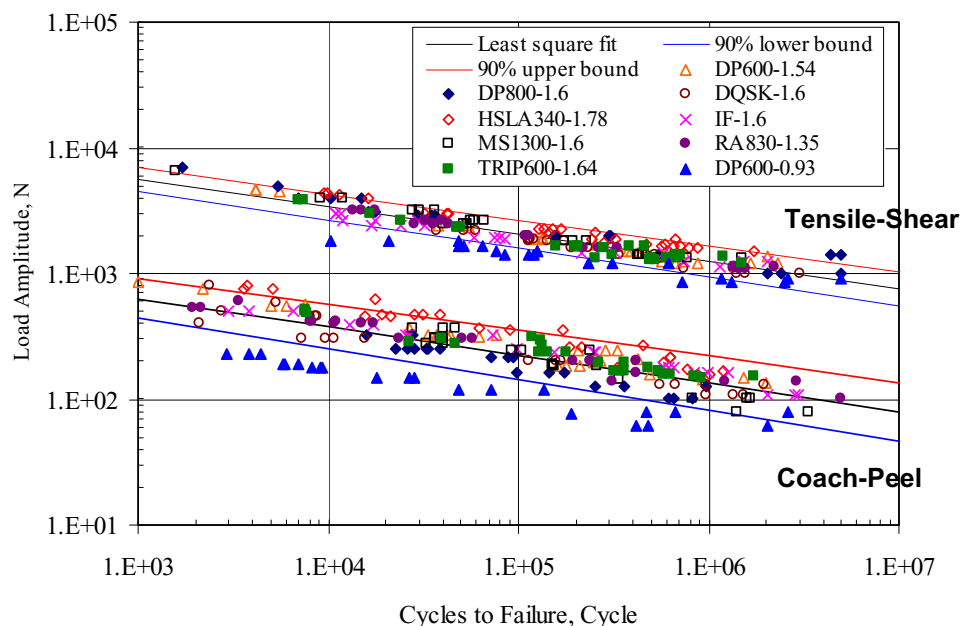


Figure 1. Fatigue results for all spot welded material (Run outs are included but not marked).

Table 1. Chemical Composition of the Steels Tested.

	IF	DQSK	HSLA340	DP600	DP800	TRIP600	RA830	MS1300	Boron	CQSK
C	0.0049	0.0037	0.0594	0.08	0.118	0.101	0.055	0.1839	0.233	0.0468
Mn	0.187	0.109	0.378	1.74	1.913	1.47	1.206	0.445	1.194	0.202
P	0.007	0.007	0.008	0.012	0.016	0.002	0.009	0.004	0.016	0.006
S	0.007	0.008	0.004	0.003	0.005	0.001	0.001	0.01	0.007	0.008
Si	0.009	0.018	0.026	0.016	0.022	1.536	0.039	0.021	0.231	0.01
Al	0.028	0.04	0.056	0.041	0.041	0.027	0.065	0.049	0.045	0.0504
Ni	0.009	0.013	0.01	0.017	0.014	-	0.014	0.008	0.006	0.004
Mo	0.002	0.006	0.003	0.185	0.182	0.01	0.011	0.003	0	0.001
Cr	0.012	0.027	0.039	0.173	0.252	0.05	0.036	0.014	0.195	0.002
Nb	0.001	0.001	0.044	0.001	0.001	0.005	0.89	0.001	0.006	0.005
V	0.003	0.003	0.002	0.007	0.007	0.005	0.059	0.004	0.011	0.001
B	0.0001	0.0001	0.001	0.0001	0.0001	-	0.0001	0.0005	0.003	0
Ti	0.072	0.072	0.001	0.001	0.001	-	0.001	0.042	0.032	0.0023
N	0.0023	0.0028	0.0054	0.0067	0.0053	-	0.0072	0.0051	-	-

Two specimen types, Tensile Shear (TS) and Coach Peel (CP), were used to evaluate the fatigue strength of the spot welds of the various materials and are shown in Figures 2 and 3, respectively. Grip Spacers were used when testing TS specimens to ensure that the weld button was centered in the applied load path.

The test specimens were fabricated with the following welding parameters:

Squeeze time:	99 cycles
Weld time:	22 cycles
Hold time:	90 cycles
Electrode force:	6.67 kN (1500 lbs)
Cap size, truncated:	7.9 mm.

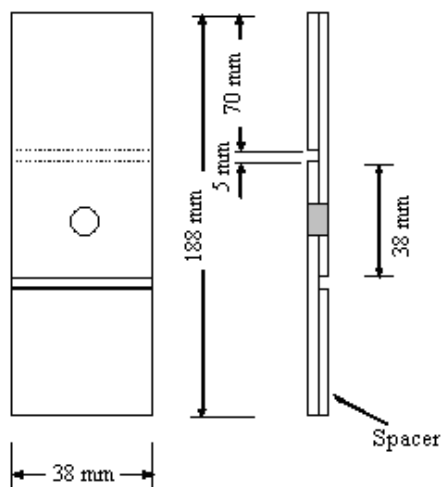


Figure 2. Schematic shape and dimensions of Tensile Shear (TS) specimen [2].

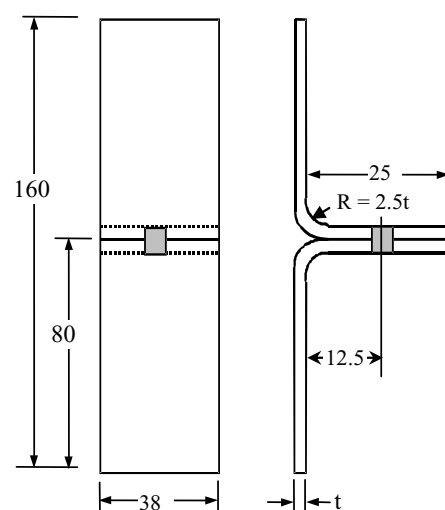


Figure 3. Schematic shape and dimensions of Coach Peel (CP) specimen [2].

An electrode force of 6.67 kN (1500 lbs) was applied when making all spot welds except for IF and DQSK grades, for which a load around 4 kN (900 lbs) was applied. To obtain consistent nugget diameter (7 mm) for all materials, the weld current and voltage were optimized for each steel grade, and the nugget diameter of the as-welded specimens was verified using pull tests and metallographic cross-sections before specimen fabrication. Tensile tests were also conducted to determine coupon strength.

Spot weld fatigue tests were conducted in load-control using a sine wave, and the test frequency ranged from 5-30 Hz, depending on maximum applied load and specimen type. Fatigue tests were conducted using a minimum of five separate load levels for an R-ratio (P_{min}/P_{max}) of $R=0.1$ and two separate load levels for $R=0.3$. Three replicate tests were conducted at each distinct load level. Specimen failure was defined as a full separation of the coupon. A "runout" cycle (or suspended test article) was set such that if the specimen reached 5×10^6 cycles, the test was stopped. Please note that one of the test labs suspended many of the tests before this point (often around 2×10^6 cycles).

FATIGUE STRENGTH VARIABILITY IN SPOT WELDS

As shown in Figure 1, scatter was observed in the fatigue test results of spot welded specimens. It is expected that fatigue test variability can be caused by many factors – among them the nugget diameter, specimen centering within the grips specimen thickness, the flange length (on CP specimens), and the hardness of the microstructure in the vicinity of the evolving crack.

Geometric Variability

To investigate the effects of the geometric variability on fatigue strength, nominal button diameter, sheet thickness, coupon width, and the distance from the center of the button to the edge of the grip were measured. Button sizes were inferred from weld tip indents and are not actual weld diameters. The measured geometric dimensions are shown in Table 2.

In Table 2, "STDEV" stands for the sample standard deviation. The parenthetical numbers in the specimen "Type" column

represent the number of measured specimens. In harder metals, grip faces often did not leave knurling marks on the specimen surfaces, making measurement of the distance from nugget center to grips (Center To Grip) impossible – these materials are labeled with "Invisible".

Nominal Weld Nugget Diameter

The average nominal nugget diameter of mild steel (IF and DQSK) and high strength low alloy steel (HSLA340) weld nuggets are larger than those of AHSS, and this material variability is shown in Figure 4. However, the difference is within 10% for TS and 12% for CP specimens. The effect of nugget diameter on the fatigue strength of DQSK and DP800 spot welds is shown in Figure 5. Aside from nominal nugget diameter, DQSK and DP800 have nearly identical dimensions (as can be seen in Table 2). The effect of nominal nugget diameter on fatigue strength seems minimal in these two materials, although the difference in the nugget diameters was not large.

Center to Grip Distance

Large variation is observed in the average center to grip (CTG) distance measured in CP specimens, as shown in Figure 6 (and Table 2). Normalized CTG in percentage was calculated by dividing the difference between Target CTG and Measured CTG by Target CTG ($100(T - M) / T$). The standard deviation of the CTG is larger for CP specimens than for TS specimens. The specimens were "more or less" centered, but there was inherent variability in the specimen fabrication. Given the variability, the effect of CTG on spot welds fatigue strength seems minimal as shown in Figure 7. The significant difference between the average CTG distance for DP600 (1.53 mm-thick) and RA830 (1.39 mm-thick) specimens does not appear to have a significant influence the fatigue life. Further, a difference in CTG of 6 mm was observed between DP600-1.53 and RA830 CP specimens, and, again, no substantial difference in fatigue performance was visible. Since the data set in Figure 7 also includes the sheet thickness effects, it was assumed that the very small variations observed in the data set arose largely from the thickness differences and not CTG distance.

Table 2. Geometric Variability of TS and CP specimens

Materials	Type	Dia. mm	Dia. STDEV	t mm	t STDEV	Width mm	Width STDEV	Center To Grip mm			
								Top	STDEV	Bottom	STDEV
DP600 - 0.83	TS (17)	7.19	0.19	0.94	0.02	38.10	0.15	55.87	1.43	55.62	1.60
	CP (18)	7.29	0.09	0.93	0.02	38.37	0.06	49.61	6.57	53.96	4.23
DP600GI-1.53	TS (26)	6.95	0.10	1.49	0.01	39.35	0.13	43.97	1.69	44.22	1.17
	CP (24)	7.16	0.29	1.54	0.04	38.91	0.14	40.82	1.99	41.40	2.75
TRIP600 Bare	TS (20)	7.23	0.11	1.61	0.02	39.42	0.19	51.73	2.36	49.57	3.23
	CP (23)	7.10	0.13	1.60	0.03	39.38	0.38	Invisible			
HSLA340 - 1.78	TS (19)	7.32	0.15	1.77	0.02	38.95	0.26	45.57	1.04	45.64	1.64
	CP (22)	7.50	0.15	1.80	0.02	38.75	0.18	42.50	8.30	43.99	8.34
RA830	TS (16)	7.26	0.14	1.37	0.01	38.70	0.24	57.90	2.59	58.10	2.48
	CP (17)	7.16	0.09	1.39	0.02	39.36	0.28	48.95	7.70	45.95	7.89
MS1300	TS (15)	7.21	0.30	1.62	0.03	38.90	0.47	Invisible			
	CP (17)	7.02	0.10	1.63	0.06	38.73	0.62	Invisible			
IF	TS (20)	7.60	0.25	1.63	0.02	38.38	0.14	54.76	1.36	54.96	3.34
	CP (20)	7.69	0.15	1.64	0.04	38.34	0.38	42.63	3.59	41.52	3.61
DQSK	TS (21)	7.60	0.18	1.61	0.01	38.60	0.20	55.11	1.08	55.04	0.71
	CP (20)	8.00	0.18	1.63	0.02	38.67	0.18	52.12	10.56	50.10	8.92
DP800	TS (15)	7.14	0.31	1.59	0.01	39.37	0.17	55.76	1.11	55.06	1.33
	CP (17)	7.02	0.17	1.64	0.02	39.81	0.52	Invisible			
CQSK	TS (27)	6.89	0.09	1.80	0.03	38.30	0.16	47.29	3.85	45.89	4.45
	CP (24)	6.92	0.09	1.76	0.01	38.35	0.14	44.40	8.86	45.03	8.04
BORON	TS (20)	7.23	0.19	1.69	0.02	38.38	0.49	47.07	6.02	44.52	2.46
	CP (7)	7.04	0.09	1.47	0.01	37.92	0.09	Invisible			

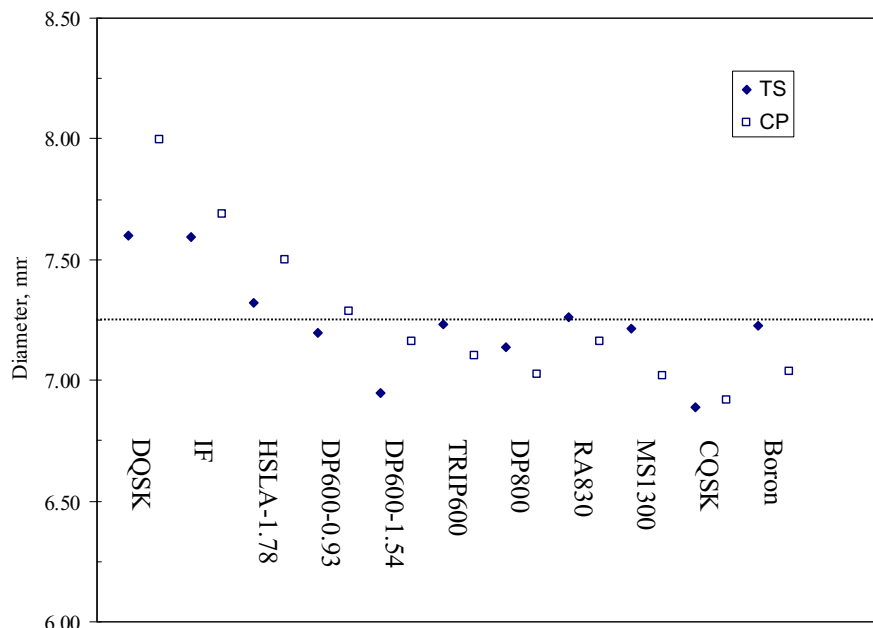


Figure 4. Spot weld nugget diameters for the various specimens tested.

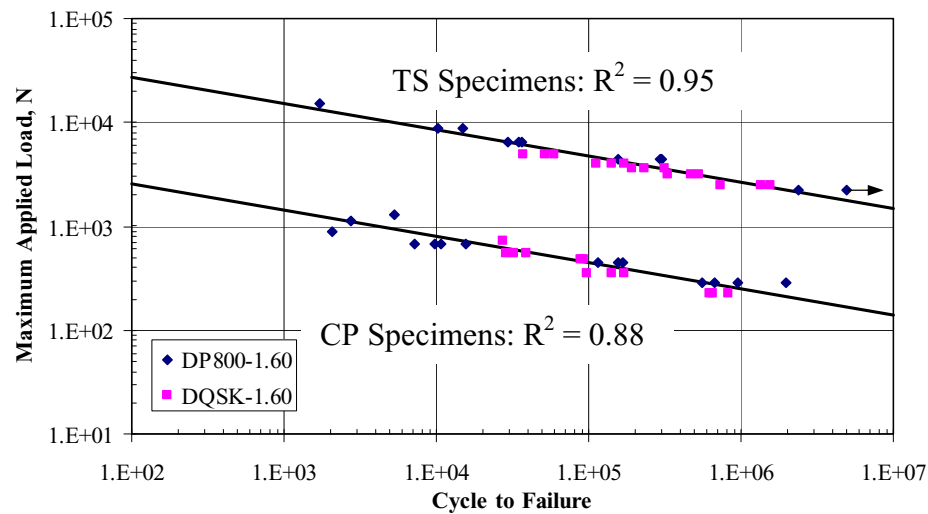


Figure 5. Effect of nugget diameter on fatigue strength of DP800 and DQSK spot welds.

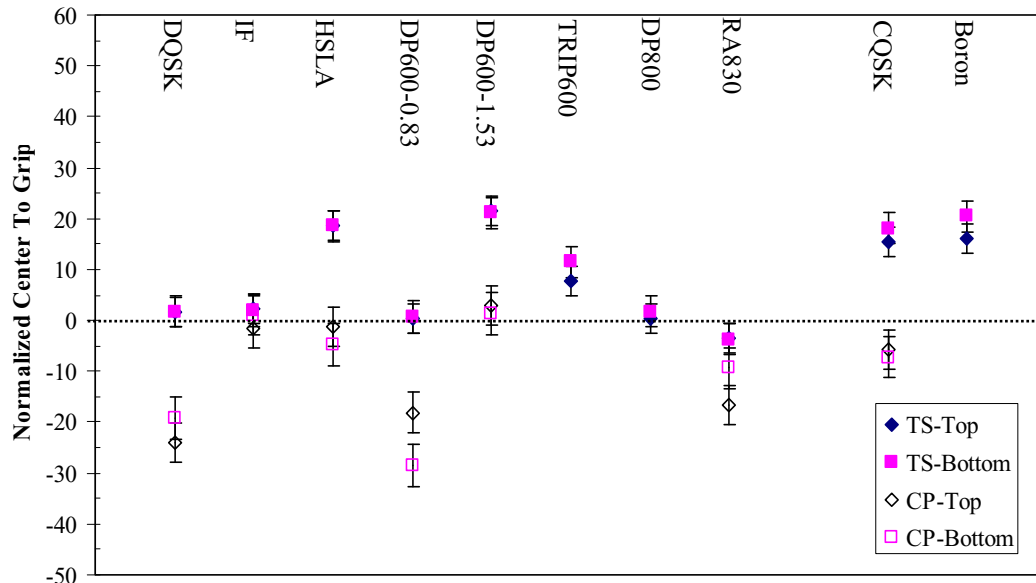


Figure 6. Variation for center to grip distance.

Sheet Thickness

Although the original study had targeted steel thickness at 1.60mm, the real material thicknesses ranged from as low as 1.23 mm to 1.80 mm. Two additional iterations (HSLA 350-1.00mm & DP600-0.93mm) were added to examine thickness sensitivity. Unfortunately, the failed HSLA specimens were unavailable for study. However, the thin and thick DP600 TS specimens were measured at 0.94 mm and 1.49 mm thick respectively. Similarly, the thin and thick CP specimens were measured at 0.93 mm

and 1.54 mm, respectively. Figure 8 shows the effect of sheet thickness on fatigue strength of spot welds. The effect of sheet thickness is far more severe in CP specimens than in TS specimens.

Flange Length in CP specimens

The greatest degree of geometric variability was observed in the CP specimens since two difficult-to-control 90-degree bends had to be made and the coupon halves aligned, clamped, and then welded. Further, during CP