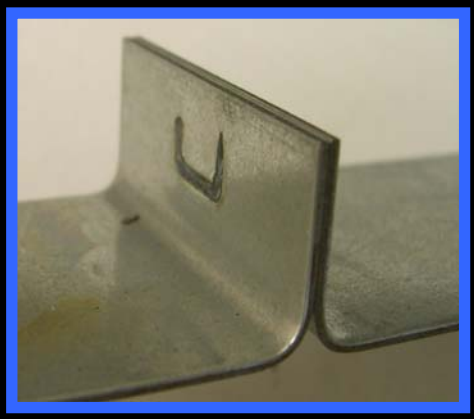

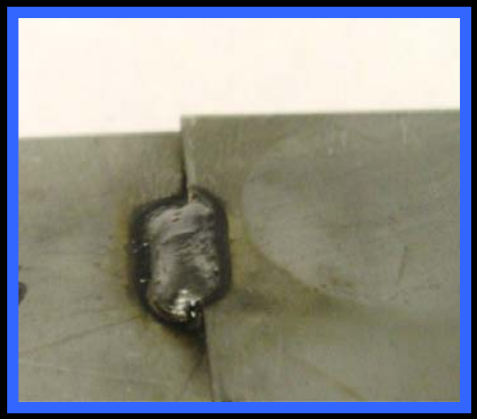

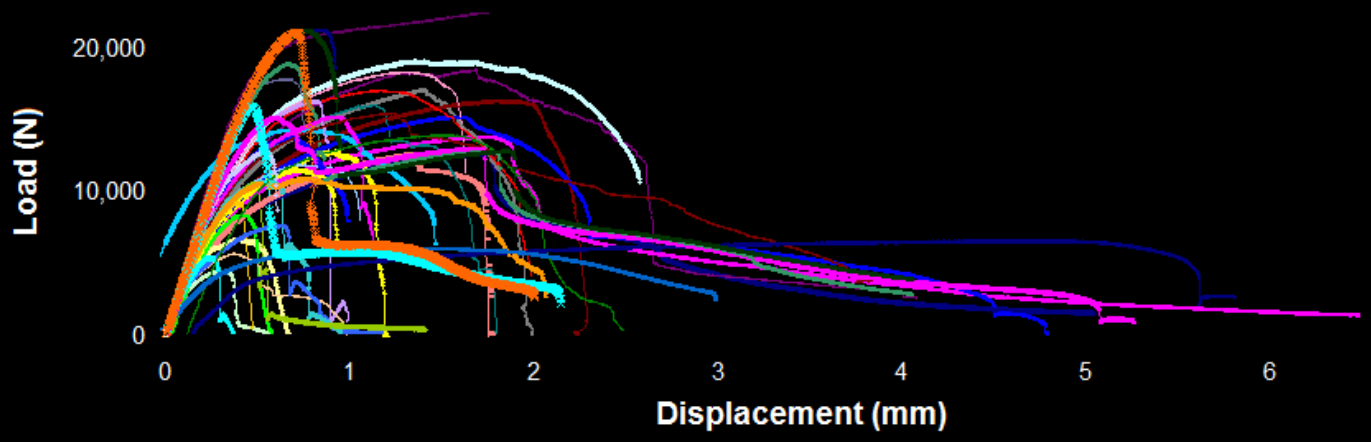

Joint Efficiency and Weld Repair Project - Phase II

Executive Summary

A comparative study of joint efficiency, energy, and stiffness for advanced high strength steel joining processes

A/S P Auto/Steel Partnership

10/2009

Auto/Steel Partnership

A/SP Joining Technology Committee
Joint Efficiency and Repair Welding Phase II

Executive Summary

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This work is the second phase of a study on various grades of steels, to quantify peak load, joint efficiency, energy, and joint stiffness for a variety of joining methods. The data allows comparisons to be made for production welding/joining processes and repair substitutions. Several modifications were made to the test methodology of the previously reported Phase I Joint Efficiency and Repair Welding study. These modifications included studying both lap and coach joints and reducing the specimen overlap distance. Weld sizes were also adjusted to more closely represent typical production joints. Several new processes were used, and some previous processes were omitted. The data from this study (Phase I and II) is aimed at providing a baseline reference for a wide variety of welding and joining processes and material combinations.

Materials studied in this phase were 1.2 mm galvanized mild steel, 1.2 mm electro-galvanized High Strength Low Alloy Steel (HSLA), 1.2mm galvanized DP600, 1.0 mm galvannealed DP780, and 1.0 mm electro-galvanized M190. A variety of joining processes were used in this study. The process categories included resistance spot welding, gas metal arc welding, arc brazing, laser welding,laser brazing, laser MIG welding, mechanical fasteners, and adhesive bonding. Lap shear and coach peel joints were studied. Test specimens were made to reflect typical joints consistent with automotive industry acceptance criteria. Welding procedures were qualified prior to producing specimens for testing.

Load/displacement curves were generated using a tensile test machine. Joint efficiency was calculated from tensile test data as the peak load of the joint divided by the peak load of the parent material, expressed as a percentage. Energy was calculated as the area under the curve up to peak load. Joint stiffness was calculated as the slope of the best fit line in the elastic region of the load/displacement curve. For comparison purposes, joint energy and stiffness were normalized to the parent metal values and expressed as percentages.

It was observed that the materials tested are weldable and joinable by all of the welding, brazing, and adhesive processes used. Due to process limitations and the low ductility of the highest strength steels, certain mechanical fasteners may not be compatible with some grades and gauges of AHSS.

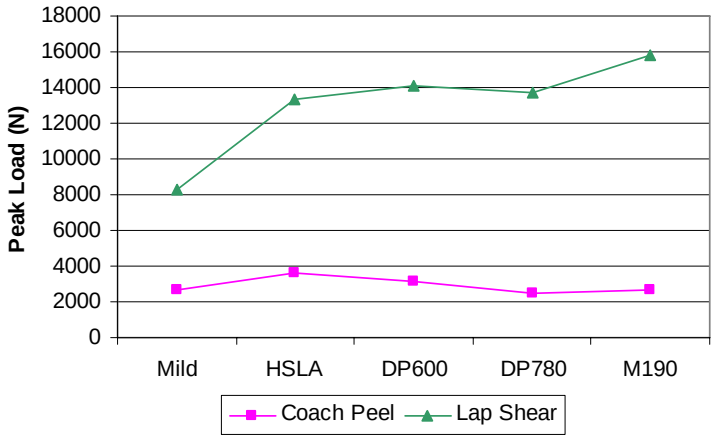
In general, there was no correlation between joint efficiency, normalized energy, and normalized stiffness. Some processes, joint configurations and material combinations have high joint efficiency and energy, while others result in high joint efficiency but low energy. Few processes showed high values for all metrics across all materials and joint configurations.

It was observed that peak loads tended to increase, on average, as material strength increased for lap joints. However, joint efficiency generally decreased as material strength increased. Therefore, joint strength did not increase in proportion to parent material strength increase for most of the processes and materials studied.

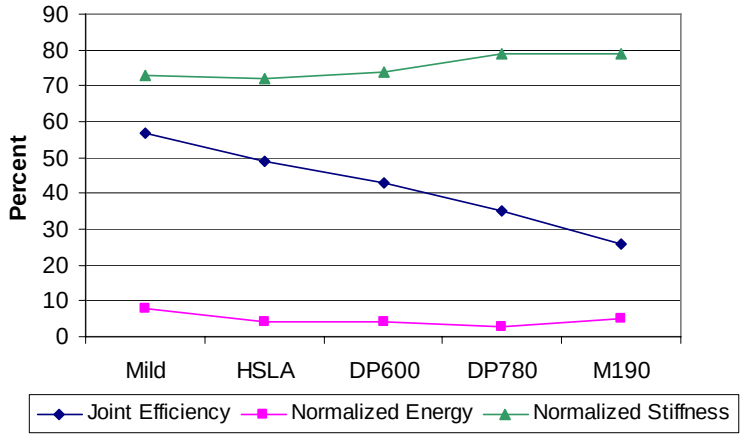
Coach joints generally showed lower joint efficiency and stiffness than lap joints. Some processes that provided comparatively high joint efficiency in lap joints showed very low joint efficiency in coach joints. The opposite was also true.

Average normalized stiffness was similar for all materials. Average normalized energy was highest in mild steel, but similar among AHSS.

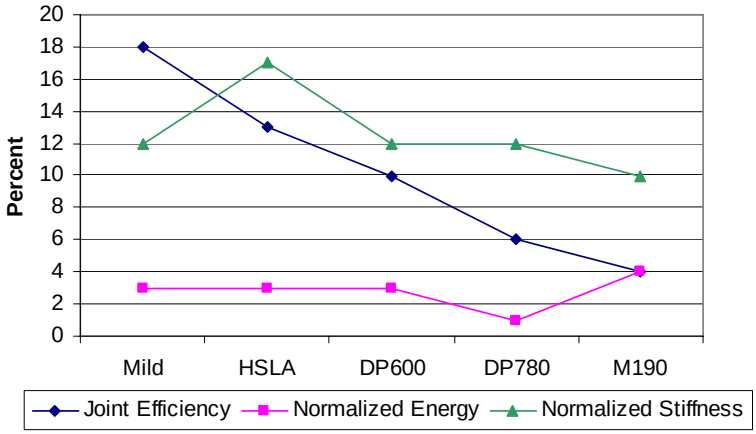
While many generalizations can be made, metrics vary significantly. Therefore, process and material combinations should be selected based on the required performance, joint design, and cost.



Average Peak Loads (All Processes Combined)



Lap Shear Average Joint Efficiency, Normalized Energy and Stiffness (All Processes Combined)



Coach Peel Average Joint Efficiency, Normalized Energy and Stiffness (All Processes Combined)

Joint Efficiency Observations

Adhesive joints, both alone and with RSW/SPR, along with 25mm laser welds and 25mm GMAW joints had the highest joint efficiency for lap joints. The lowest joint efficiency was achieved with rivets and lap fillet brazed joints. In general, resistance spot welds, arc spot welds, and 15mm GMAW lap fillets had similar joint efficiency.

For coach joints, laser lap welds had joint efficiency nearly double that of other processes. Coach joints typically had joint efficiencies which were 70% or less than lap joints for like processes. The difference was more substantial in higher strength steels. However, some processes which showed low joint efficiency for lap joints had comparatively higher joint efficiency for coach joints. The opposite was also observed.

Normalized Energy Observations

For lap joints in advanced high strength steels, 25mm GMAW and laser welds, starting schedule resistance spot welds, and Hemlok rivets generally had the highest normalized energy. For mild steel, SPR/adhesive joints had normalized energy nearly double that of other processes.

For coach joints, laser lap welds showed normalized energy close to double that of other processes. Resistance spot welds, both alone and with adhesives also had high normalized energy.

Some processes showed high normalized energy for lap joints and low normalized energy for coach joints.

In this study, all energy values were calculated up to peak load, according to AWS test methods. It is important to note that many of the coach peel SPR/RSW adhesive joints had two load spikes in the load/displacement curve. One occurred at very short displacement and the other at longer displacement. Energy was only calculated up to peak load, whether it was at short displacement or longer displacement. Mild steel RSW/Adhesive and SPR/Adhesive joints showed similar areas under the load/displacement curves up to complete fracture. However, there is a difference in peak load locations on the curves. This resulted in a normalized energy calculation of 0% for the RSW/Adhesive joint and a normalized energy of 2% for the SPR/Adhesive joint. Low energy values for some processes may be due to the calculation method and not poor joint performance. Note that the highest normalized energy for all processes in mild steel coach peel joints was 7%, so the difference between 0% and 2% is significant.

Normalized Stiffness Observations

For lap joints, adhesive bonded joints showed the highest normalized stiffness for all materials. Laser 25 mm welds and GMAW 25 mm welds also had high normalized stiffness. Resistance spot welds and mechanical fasteners typically showed the lowest normalized stiffness.

For all materials, adhesive bonded joints had much higher normalized stiffness than all other processes for coach joints. This is due to the larger bonded area in the overlap. Coach joints showed lower stiffness than lap joints for most processes.

Phase I to Phase II Comparisons

Mild steel, DP600, and DP780 were used in both Phase I and Phase II studies. Many of the same processes were also used for both studies. For common materials, joint efficiency for like processes was very close in both studies. Adhesive joints were typically higher in Phase 1, due to larger bonded area.

There is a substantial difference in normalized energy between Phase I and Phase II joints. This is due to the higher displacement of Phase II parent metal samples. The parent metal coupon length was 175mm for Phase I and 195mm for Phase II. Accounting for grip lengths, the effective test lengths were 75mm for Phase I and 95mm for Phase II parent material coupons. Peak loads were similar in both studies, while higher displacement was seen in Phase II. This resulted in higher parent metal energy values. Normalizing the joint peak loads with respect to higher parent metal energy caused the Phase II normalized energy calculations to be lower.

Auto/Steel Partnership

Mild Lap Shear

Joining Process	Joint Efficiency	Normalized Energy	Normalized Stiffness	Peak Load (N)	Energy (J)	Stiffness (N/mm)	Displacement at Peak Load (mm)
Parent Metal	100%	100%	100%	14533	534	40660	40.9
A/SP RSW Starting Schedule (AC)	45%	3%	58%	6516	18	23588	3.3
A/SP RSW Starting Schedule (DC)	48%	5%	35%	6968	24	14277	4.2
Arc Braze - Plug Joint (10mm hole)	56%	6%	74%	8204	32	30224	4.5
Arc Braze (15mm lap fillet)	36%	1%	58%	5220	4	23438	1.0
Arc Braze (20mm lap fillet)	43%	1%	76%	6178	7	30857	1.4
Arc Braze (25mm lap fillet)	54%	3%	77%	7855	17	31322	2.5
Fracture Toughened Adhesive A	88%	15%	93%	12731	83	37960	7.8
Fracture Toughened Adhesive B	76%	7%	94%	10984	35	38401	3.8
Fracture Toughened Adhesive C	71%	5%	94%	10284	27	38416	3.1
GMAW - Arc Spot	51%	4%	78%	7381	22	31857	3.4
GMAW - Plug Weld (10mm hole)	58%	6%	71%	8429	33	28908	4.6
GMAW (AWS D8.8M - 15mm fillet)	46%	2%	72%	6647	11	29371	2.1
GMAW (AWS D8.8M - 20mm fillet)	58%	4%	81%	8456	24	32856	3.3
GMAW (AWS D8.8M - 25mm fillet)	68%	8%	81%	9908	42	33076	5.1
Hemlok Rivet	24%	5%	15%	3494	25	5938	9.1
Laser (15mm lap fillet)	38%	2%	59%	5595	9	24120	2.1
Laser (15mm lap)	48%	3%	69%	6914	18	28126	3.2
Laser (20mm lap fillet)	54%	4%	68%	7814	23	27816	3.6
Laser (20mm lap)	60%	6%	71%	8649	34	28882	4.7
Laser (25mm lap fillet)	65%	8%	75%	9379	43	30681	5.5
Laser (25mm lap)	70%	10%	83%	10139	52	33764	6.2
Laser (staple geometry)	55%	7%	68%	7961	37	27595	5.4
Laser Braze (15mm lap fillet)	31%	0%	64%	4478	2	25903	0.7
Laser Braze (20mm lap fillet)	40%	1%	69%	5786	4	28209	0.9
Laser Braze (25mm lap fillet)	46%	1%	73%	6657	5	29683	0.8
Laser Mig (15mm lap fillet)	47%	2%	65%	6810	12	26591	2.0
Laser Mig (20mm lap fillet)	59%	4%	75%	8575	24	30350	3.3
Laser Mig (25mm lap fillet)	66%	6%	69%	9552	33	27876	4.1
Manual GMAW (AWS D8.8M - 15mm fillet)	46%	2%	71%	6703	11	29036	1.9
Manual GMAW (AWS D8.8M - 20mm fillet)	59%	5%	77%	8583	27	31290	3.7
Manual GMAW (AWS D8.8M - 25mm fillet)	68%	8%	90%	9930	44	36455	5.2
Plasma Braze (15mm lap fillet)	46%	2%	72%	6681	13	29099	2.2
Plasma Braze (20mm lap fillet)	53%	4%	73%	7720	20	29718	3.1
Plasma Braze (25mm lap fillet)	58%	4%	81%	8467	21	32856	2.9
Resistance Spot Weld (AWS D8.1M)	42%	3%	52%	6073	16	21250	3.2
RSW/Adhesive A	76%	8%	82%	11031	42	33232	4.5
RSW/Adhesive B	77%	8%	89%	11195	43	36318	4.6
RSW/Adhesive C	59%	7%	84%	8627	35	34326	4.4
Self Pierce Rivet	23%	1%	34%	3397	6	13743	2.2
SPR/Adhesive A	94%	24%	97%	13715	129	39573	11.2
SPR/Adhesive B	91%	19%	94%	13183	103	38410	9.3
SPR/Adhesive C	74%	7%	93%	10769	35	37751	3.8

Mild Coach Peel

Joining Process	Joint Efficiency	Normalized Energy	Normalized Stiffness	Peak Load (N)	Energy (J)	Stiffness (N/mm)	Displacement at Peak Load (mm)
Parent Metal	100%	100%	100%	14533	534	40660	40.9
A/SP RSW Starting Schedule (AC)	16%	3%	2%	2288	15	945	11.7
A/SP RSW Starting Schedule (DC)	17%	3%	2%	2430	17	725	13.3
Arc Braze - Plug Joint (10mm hole)	18%	3%	3%	2558	15	1079	9.2
Fracture Toughened Adhesive A	17%	0%	34%	2493	1	13844	0.4
Fracture Toughened Adhesive B	9%	0%	23%	1352	0	9422	0.2
Fracture Toughened Adhesive C	11%	0%	24%	1670	0	9925	0.3
GMAW - Arc Spot	13%	2%	3%	1840	10	1100	8.6
GMAW - Plug Weld (10mm hole)	17%	3%	1%	2473	18	383	13.9
Hemlok Rivet	9%	1%	1%	1251	6	468	7.4
Laser (15mm lap)	33%	6%	1%	4751	32	337	18.9
Laser (20mm lap)	47%	7%	3%	6824	38	1049	18.9
Laser (25mm lap)	43%	7%	3%	6295	35	1093	18.1
Laser (staple geometry)	30%	5%	1%	4365	25	494	13.8
Resistance Spot Weld (AWS D8.1M)	10%	2%	2%	1511	10	828	10.4
RSW/Adhesive A	14%	0%	28%	2007	0	11459	0.3
RSW/Adhesive B	14%	3%	16%	1993	15	6347	12.3
RSW/Adhesive C	16%	4%	23%	2375	19	9254	13.4
Self Pierce Rivet	10%	2%	2%	1463	10	778	9.7
SPR/Adhesive A	12%	2%	30%	1775	13	12347	9.9
SPR/Adhesive B	12%	0%	26%	1767	0	10684	0.2
SPR/Adhesive C	11%	2%	25%	1639	12	10221	9.8

HSLA Lap Shear

Joining Process	Joint Efficiency	Normalized Energy	Normalized Stiffness	Peak Load (N)	Energy (J)	Stiffness (N/mm)	Displacement at Peak Load (mm)
Parent Metal	100%	100%	100%	27213	536	48090	21.1
A/SP RSW Starting Schedule (AC)	41%	2%	72%	11245	9	34743	1.0
A/SP RSW Starting Schedule (DC)	47%	3%	64%	12697	15	30559	1.5
Arc Braze - Plug Joint (10mm hole)	44%	1%	68%	12107	6	32497	0.6
Arc Braze (15mm lap fillet)	20%	0%	63%	5489	2	30375	0.5
Arc Braze (20mm lap fillet)	29%	1%	73%	7867	3	35308	0.6
Arc Braze (25mm lap fillet)	34%	1%	67%	9126	4	32209	0.6
Fracture Toughened Adhesive A	75%	2%	84%	20410	9	40548	0.7
Fracture Toughened Adhesive B	71%	2%	88%	19411	9	42337	0.7
Fracture Toughened Adhesive C	44%	1%	78%	12080	4	37652	0.5
GMAW - Arc Spot	39%	1%	69%	10523	7	33027	0.7
GMAW - Plug Weld (10mm hole)	51%	1%	78%	13756	8	37691	0.8
GMAW (AWS D8.8M - 15mm fillet)	40%	1%	68%	10957	6	32777	0.7
GMAW (AWS D8.8M - 20mm fillet)	48%	1%	72%	13029	8	34453	0.8
GMAW (AWS D8.8M - 25mm fillet)	61%	2%	73%	16624	12	35041	1.0
Hemlok Rivet	20%	4%	56%	5393	23	26983	4.9
Laser (15mm lap fillet)	30%	1%	63%	8242	3	30468	0.6
Laser (15mm lap)	45%	2%	72%	12126	11	34844	1.2
Laser (20mm lap fillet)	51%	3%	68%	13874	17	32902	1.6
Laser (20mm lap)	55%	4%	70%	15029	21	33835	1.8
Laser (25mm lap fillet)	61%	4%	69%	16698	23	33153	1.8
Laser (25mm lap)	68%	6%	79%	18601	31	37775	2.1
Laser (staple geometry)	51%	3%	62%	13760	16	30056	1.5
Laser Braze (15mm lap fillet)	20%	0%	62%	5423	1	29758	0.3
Laser Braze (20mm lap fillet)	26%	0%	69%	7128	2	33241	0.4
Laser Braze (25mm lap fillet)	31%	0%	74%	8551	3	35734	0.3
Laser Mig (15mm lap fillet)	50%	2%	73%	13480	9	35001	0.7
Laser Mig (20mm lap fillet)	60%	2%	73%	16453	13	35125	1.1
Laser Mig (25mm lap fillet)	68%	5%	75%	18537	24	35982	1.7
Manual GMAW (AWS D8.8M - 15mm fillet)	39%	1%	66%	10675	4	31868	0.6
Manual GMAW (AWS D8.8M - 20mm fillet)	51%	2%	72%	13794	11	34635	1.1
Manual GMAW (AWS D8.8M - 25mm fillet)	62%	3%	73%	16937	15	35190	1.2
Plasma Braze (15mm lap fillet)	32%	0%	65%	8691	3	31282	0.5
Plasma Braze (20mm lap fillet)	39%	1%	74%	10673	3	35637	0.5
Plasma Braze (25mm lap fillet)	39%	1%	72%	10697	4	34395	0.5
Resistance Spot Weld (AWS D8.1M)	39%	2%	55%	10479	12	26471	1.4
RSW/Adhesive A	71%	2%	87%	19190	9	41996	0.7
RSW/Adhesive B	73%	2%	86%	19738	9	41224	0.7
RSW/Adhesive C	63%	1%	87%	17226	7	41781	0.6
Self Pierce Rivet	20%	1%	25%	5532	5	12057	1.2
SPR/Adhesive A	77%	2%	87%	21090	8	41634	0.7
SPR/Adhesive B	74%	1%	87%	20093	8	42071	0.6
SPR/Adhesive C	53%	1%	85%	14430	3	41051	0.4

HSLA Coach Peel

Joining Process	Joint Efficiency	Normalized Energy	Normalized Stiffness	Peak Load (N)	Energy (J)	Stiffness (N/mm)	Displacement at Peak Load (mm)
Parent Metal	100%	100%	100%	27213	536	48090	21.1
A/SP RSW Starting Schedule (AC)	11%	3%	2%	2988	17	1110	9.0
A/SP RSW Starting Schedule (DC)	9%	2%	2%	2351	11	853	7.5
Arc Braze - Plug Joint (10mm hole)	7%	1%	5%	1877	6	2609	3.9
Fracture Toughened Adhesive A	14%	0%	42%	3902	1	20204	0.3
Fracture Toughened Adhesive B	11%	0%	37%	2971	0	17588	0.2
Fracture Toughened Adhesive C	11%	0%	44%	2999	0	21009	0.2
GMAW - Arc Spot	10%	2%	3%	2800	10	1519	5.1
GMAW - Plug Weld (10mm hole)	11%	3%	5%	3073	15	2390	7.1
Hemlok Rivet	9%	2%	2%	2366	12	866	7.4
Laser (15mm lap)	23%	9%	2%	6262	46	1106	17.1
Laser (20mm lap)	32%	10%	3%	8817	54	1321	17.6
Laser (25mm lap)	31%	10%	3%	8570	52	1399	17.2
Laser (staple geometry)	21%	7%	4%	5848	36	1810	12.2
Resistance Spot Weld (AWS D8.1M)	12%	4%	2%	3160	19	1085	10.2
RSW/Adhesive A	12%	0%	40%	3301	1	19085	0.3
RSW/Adhesive B	12%	4%	37%	3278	23	17589	10.2
RSW/Adhesive C	11%	4%	34%	3086	20	16432	9.8
Self Pierce Rivet	8%	2%	2%	2097	10	898	6.6
SPR/Adhesive A	9%	3%	25%	2372	15	11867	7.7
SPR/Adhesive B	9%	2%	32%	2492	11	15592	5.2
SPR/Adhesive C	8%	3%	25%	2223	14	12195	7.7

DP600 Lap Shear

Joining Process	Joint Efficiency	Normalized Energy	Normalized Stiffness	Peak Load (N)	Energy (J)	Stiffness (N/mm)	Displacement at Peak Load (mm)
Parent Metal	100%	100%	100%	32900	549	46563	19.0
A/SP RSW Starting Schedule (AC)	46%	4%	75%	14984	23	34808	2.0
A/SP RSW Starting Schedule (DC)	42%	3%	64%	13715	18	29926	1.7
Arc Braze - Plug Joint (10mm hole)	33%	1%	74%	10855	6	34269	0.8
Arc Braze (15mm lap fillet)	17%	0%	74%	5643	1	34383	0.4
Arc Braze (20mm lap fillet)	23%	1%	72%	7526	3	33413	0.6
Arc Braze (25mm lap fillet)	32%	1%	76%	10618	4	35163	0.6
Fracture Toughened Adhesive A	64%	2%	87%	21121	12	40708	0.8
Fracture Toughened Adhesive B	54%	1%	89%	17761	8	41482	0.7
Fracture Toughened Adhesive C	39%	1%	81%	12694	4	37913	0.5
GMAW - Arc Spot	42%	3%	69%	13904	14	32138	1.5
GMAW - Plug Weld (10mm hole)	47%	3%	77%	15418	14	35897	1.2
GMAW (AWS D8.8M - 15mm fillet)	36%	1%	71%	11851	6	32836	0.7
GMAW (AWS D8.8M - 20mm fillet)	42%	1%	79%	13656	6	36782	0.7
GMAW (AWS D8.8M - 25mm fillet)	56%	3%	79%	18268	17	36619	1.3
Hemlok Rivet	20%	5%	26%	6494	25	12053	4.7
Laser (15mm lap fillet)	38%	2%	66%	12538	12	30639	1.3
Laser (15mm lap)	39%	1%	73%	12715	8	34028	0.9
Laser (20mm lap fillet)	49%	4%	72%	16220	22	33540	1.8
Laser (20mm lap)	52%	3%	77%	17040	17	35852	1.4
Laser (25mm lap fillet)	49%	2%	79%	15966	13	36648	1.1
Laser (25mm lap)	56%	4%	82%	18441	24	38330	1.7
Laser (staple geometry)	46%	3%	71%	15093	18	32834	1.6
Laser Braze (15mm lap fillet)	13%	0%	62%	4385	1	28746	0.3
Laser Braze (20mm lap fillet)	20%	0%	72%	6646	2	33306	0.4
Laser Braze (25mm lap fillet)	25%	0%	76%	8259	2	35234	0.4
Laser Mig (15mm lap fillet)	43%	2%	73%	14232	9	34183	0.7
Laser Mig (20mm lap fillet)	52%	3%	75%	16996	14	34918	1.2
Laser Mig (25mm lap fillet)	58%	3%	74%	18994	19	34406	1.4
Manual GMAW (AWS D8.8M - 15mm fillet)	35%	1%	68%	11462	5	31562	0.7
Manual GMAW (AWS D8.8M - 20mm fillet)	46%	2%	74%	15089	10	34530	0.9
Manual GMAW (AWS D8.8M - 25mm fillet)	49%	2%	84%	16175	9	39069	0.8
Plasma Braze (15mm lap fillet)	16%	0%	66%	5400	1	30558	0.2
Plasma Braze (20mm lap fillet)	32%	1%	72%	10527	3	33548	0.5
Plasma Braze (25mm lap fillet)	28%	0%	75%	9104	2	34721	0.4
Resistance Spot Weld (AWS D8.1M)	38%	3%	60%	12624	16	27896	1.7
RSW/Adhesive A	64%	2%	89%	21116	10	41428	0.8
RSW/Adhesive B	57%	1%	86%	18769	8	40165	0.7
RSW/Adhesive C	46%	1%	81%	15088	6	37903	0.6
Self Pierce Rivet	18%	1%	29%	5980	6	13354	1.2
SPR/Adhesive A	69%	6%	89%	22798	31	41437	1.7
SPR/Adhesive B	64%	2%	87%	20977	9	40557	0.7
SPR/Adhesive C	48%	1%	86%	15896	4	40159	0.5

DP600 Coach Peel

Joining Process	Joint Efficiency	Normalized Energy	Normalized Stiffness	Peak Load (N)	Energy (J)	Stiffness (N/mm)	Displacement at Peak Load (mm)
Parent Metal	100%	100%	100%	32900	549	46563	19.0
A/SP RSW Starting Schedule (AC)	9%	3%	3%	3032	14	1237	7.2
A/SP RSW Starting Schedule (DC)	6%	1%	2%	1860	7	775	5.9
Arc Braze - Plug Joint (10mm hole)	5%	1%	3%	1706	3	1218	2.5
Fracture Toughened Adhesive A	9%	0%	25%	2833	1	11686	0.3
Fracture Toughened Adhesive B	6%	0%	29%	2014	0	13520	0.2
Fracture Toughened Adhesive C	6%	0%	22%	2109	0	10449	0.3
GMAW - Arc Spot	7%	2%	3%	2411	10	1324	5.6
GMAW - Plug Weld (10mm hole)	9%	2%	4%	2887	12	1667	6.0
Hemlok Rivet	9%	3%	2%	3029	14	1087	7.1
Laser (15mm lap)	16%	7%	2%	5235	40	1145	14.7
Laser (20mm lap)	20%	9%	3%	6462	47	1286	15.4
Laser (25mm lap)	19%	9%	3%	6327	48	1310	15.4
Laser (staple geometry)	15%	5%	4%	4892	27	1954	9.4
Resistance Spot Weld (AWS D8.1M)	8%	2%	2%	2753	14	1080	7.7
RSW/Adhesive A	9%	3%	19%	2957	15	9034	7.5
RSW/Adhesive B	10%	3%	29%	3363	18	13698	8.2
RSW/Adhesive C	10%	3%	25%	3287	18	11657	8.4
Self Pierce Rivet	7%	2%	2%	2149	8	795	5.8
SPR/Adhesive A	8%	0%	26%	2653	0	12146	0.3
SPR/Adhesive B	7%	2%	27%	2439	9	12599	4.8
SPR/Adhesive C	6%	1%	14%	1970	6	6668	3.8

Auto/Steel Partnership

DP780 Lap Shear

Joining Process	Joint Efficiency	Normalized Energy	Normalized Stiffness	Peak Load (N)	Energy (J)	Stiffness (N/mm)	Displacement at Peak Load (mm)
Parent Metal	100%	100%	100%	39095	653	38718	18.5
A/SP RSW Starting Schedule (AC)	29%	1%	67%	11476	6	26130	0.8
A/SP RSW Starting Schedule (DC)	37%	2%	71%	14326	12	27347	1.2
Arc Braze - Plug Joint (10mm hole)	31%	1%	75%	12281	10	28946	1.1
Arc Braze (15mm lap fillet)	18%	0%	80%	7060	2	31044	0.4
Arc Braze (20mm lap fillet)	21%	0%	75%	8287	3	28874	0.5
Arc Braze (25mm lap fillet)	29%	0%	78%	11339	3	30110	0.5
Fracture Toughened Adhesive A	43%	1%	94%	16704	4	36337	0.5
Fracture Toughened Adhesive B	35%	0%	93%	13807	3	35903	0.4
Fracture Toughened Adhesive C	31%	0%	89%	11952	2	34479	0.4
GMAW - Arc Spot	28%	1%	71%	11104	4	27606	0.5
GMAW - Plug Weld (10mm hole)	32%	1%	74%	12336	8	28475	0.9
GMAW (AWS D8.8M - 15mm fillet)	29%	1%	76%	11335	4	29502	0.6
GMAW (AWS D8.8M - 20mm fillet)	40%	1%	84%	15810	7	32616	0.7
GMAW (AWS D8.8M - 25mm fillet)	50%	2%	87%	19562	12	33559	1.0
Hemlok Rivet	18%	2%	53%	6953	14	20655	2.6
Laser (15mm lap fillet)	26%	1%	68%	10179	5	26496	0.7
Laser (15mm lap)	35%	1%	76%	13735	8	29508	0.9
Laser (20mm lap fillet)	33%	1%	77%	12728	5	29772	0.7
Laser (20mm lap)	43%	2%	82%	16863	12	31604	1.1
Laser (25mm lap fillet)	39%	1%	83%	15215	8	31957	0.8
Laser (25mm lap)	53%	3%	89%	20633	19	34362	1.3
Laser (staple geometry)	42%	2%	73%	16276	13	28207	1.2
Laser Braze (15mm lap fillet)	13%	0%	70%	5223	1	27199	0.3
Laser Braze (20mm lap fillet)	22%	0%	76%	8425	2	29246	0.4
Laser Braze (25mm lap fillet)	21%	0%	82%	8075	1	31593	0.2
Laser Mig (15mm lap fillet)	39%	1%	75%	15193	8	29190	0.3
Laser Mig (20mm lap fillet)	46%	1%	80%	18136	9	31166	0.9
Laser Mig (25mm lap fillet)	59%	3%	83%	23038	22	32217	1.4
Manual GMAW (AWS D8.8M - 15mm fillet)	30%	0%	77%	11705	3	29847	0.5
Manual GMAW (AWS D8.8M - 20mm fillet)	37%	1%	82%	14304	5	31758	0.6
Manual GMAW (AWS D8.8M - 25mm fillet)	54%	2%	85%	20983	16	32877	1.1
Plasma Braze (15mm lap fillet)	25%	0%	73%	9623	2	28190	0.4
Plasma Braze (20mm lap fillet)	18%	0%	78%	6985	1	30189	0.3
Plasma Braze (25mm lap fillet)	25%	0%	80%	9686	2	30799	0.4
Resistance Spot Weld (AWS D8.1M)	32%	1%	63%	12606	10	24204	1.1
RSW/Adhesive A	40%	1%	87%	15638	4	33608	0.5
RSW/Adhesive B	33%	2%	81%	13084	10	31354	1.1
RSW/Adhesive C	33%	2%	75%	12811	10	28884	1.1
Self Pierce Rivet	13%	1%	35%	5208	5	13484	1.3
SPR/Adhesive A	45%	1%	98%	17657	5	37777	0.5
SPR/Adhesive B	40%	1%	94%	15811	4	36522	0.5
SPR/Adhesive C	38%	1%	92%	14922	4	35570	0.5

DP780 Coach Peel

Joining Process	Joint Efficiency	Normalized Energy	Normalized Stiffness	Peak Load (N)	Energy (J)	Stiffness (N/mm)	Displacement at Peak Load (mm)
Parent Metal	100%	100%	100%	39095	653	38718	18.5
A/SP RSW Starting Schedule (AC)	4%	1%	1%	1514	4	537	4.6
A/SP RSW Starting Schedule (DC)	4%	1%	2%	1586	4	773	4.2
Arc Braze - Plug Joint (10mm hole)	4%	0%	4%	1599	3	1709	2.3
Fracture Toughened Adhesive A	8%	0%	35%	3060	1	13369	0.3
Fracture Toughened Adhesive B	5%	0%	24%	1992	1	9203	0.4
Fracture Toughened Adhesive C	5%	0%	29%	1779	0	11105	0.2
GMAW - Arc Spot	4%	1%	2%	1630	4	772	3.9
GMAW - Plug Weld (10mm hole)	6%	1%	4%	2278	7	1368	4.4
Hemlok Rivet	9%	2%	2%	3377	16	736	8.1
Laser (15mm lap)	8%	3%	2%	3172	22	655	11.8
Laser (20mm lap)	10%	5%	2%	3924	30	805	13.2
Laser (25mm lap)	11%	5%	2%	4259	33	846	13.6
Laser (staple geometry)	10%	3%	3%	4054	19	1218	8.2
Resistance Spot Weld (AWS D8.1M)	6%	1%	2%	2282	8	758	6.0
RSW/Adhesive A	5%	1%	23%	2068	9	8796	6.0
RSW/Adhesive B	7%	2%	20%	2696	11	7601	6.2
RSW/Adhesive C	5%	0%	30%	2025	0	11590	0.3
Self Pierce Rivet	4%	1%	2%	1729	7	671	5.4
SPR/Adhesive A	6%	1%	35%	2263	8	13731	4.6
SPR/Adhesive B	5%	1%	31%	2082	6	12120	4.0
SPR/Adhesive C	5%	2%	7%	1888	10	2821	7.5

Auto/Steel Partnership

M190 Lap Shear

Joining Process	Joint Efficiency	Normalized Energy	Normalized Stiffness	Peak Load (N)	Energy (J)	Stiffness (N/mm)	Displacement at Peak Load (mm)
Parent Metal	100%	100%	100%	60109	269	38843	5.5
A/SP RSW Starting Schedule (AC)	24%	2%	72%	14538	6	27981	0.7
A/SP RSW Starting Schedule (DC)	27%	3%	71%	16013	9	27723	0.9
Arc Braze - Plug Joint (10mm hole)	17%	2%	79%	9975	5	30793	0.7
Arc Braze (15mm lap fillet)	10%	0%	74%	5982	1	28755	0.3
Arc Braze (20mm lap fillet)	13%	1%	74%	7892	2	28872	0.4
Arc Braze (25mm lap fillet)	18%	1%	77%	10791	3	29720	0.5
Fracture Toughened Adhesive A	40%	4%	95%	24023	10	36781	0.7
Fracture Toughened Adhesive B	30%	3%	91%	17974	7	35271	0.7
Fracture Toughened Adhesive C	27%	2%	91%	16091	6	35161	0.6
GMAW - Arc Spot	18%	3%	71%	11082	9	27570	1.1
GMAW - Plug Weld (10mm hole)	26%	5%	80%	15819	12	31077	1.1
GMAW (AWS D8.8M - 15mm fillet)	23%	2%	77%	13815	6	29798	0.7
GMAW (AWS D8.8M - 20mm fillet)	28%	3%	81%	16724	7	31470	0.7
GMAW (AWS D8.8M - 25mm fillet)	31%	3%	83%	18588	9	32067	0.8
Hemlok Rivet	14%	5%	55%	8165	14	21472	2.1
Laser (15mm lap fillet)	17%	1%	74%	10258	2	28641	0.4
Laser (15mm lap)	24%	2%	77%	14426	6	29767	0.7
Laser (20mm lap fillet)	23%	2%	78%	13681	5	30196	0.6
Laser (20mm lap)	29%	3%	84%	17279	7	32702	0.7
Laser (25mm lap fillet)	32%	4%	85%	19023	11	32930	0.9
Laser (25mm lap)	34%	5%	78%	20225	14	30254	1.1
Laser (staple geometry)	29%	3%	74%	17298	9	28705	0.8
Laser Braze (15mm lap fillet)	10%	1%	69%	6132	2	26661	0.4
Laser Braze (20mm lap fillet)	14%	1%	78%	8681	2	30250	0.4
Laser Braze (25mm lap fillet)	15%	1%	79%	8916	2	30689	0.4
Laser Mig (15mm lap fillet)	25%	2%	80%	15125	6	31122	0.5
Laser Mig (20mm lap fillet)	27%	3%	78%	16108	7	30322	0.7
Laser Mig (25mm lap fillet)	33%	4%	77%	19852	10	29887	0.9
Manual GMAW (AWS D8.8M - 15mm fillet)	20%	1%	76%	11952	4	29595	0.5
Manual GMAW (AWS D8.8M - 20mm fillet)	27%	3%	81%	16390	7	31507	0.7
Manual GMAW (AWS D8.8M - 25mm fillet)	34%	4%	86%	20160	10	33493	0.8
Plasma Braze (15mm lap fillet)	17%	1%	73%	10041	3	28373	0.5
Plasma Braze (20mm lap fillet)	20%	1%	76%	12025	4	29459	0.5
Plasma Braze (25mm lap fillet)	20%	1%	76%	12110	3	29452	0.5
Resistance Spot Weld (AWS D8.1M)	25%	3%	69%	15194	8	26664	0.8
RSW/Adhesive A	39%	4%	91%	23349	10	35229	0.8
RSW/Adhesive B	35%	4%	86%	21071	10	33522	0.8
RSW/Adhesive C	34%	3%	87%	20580	9	33648	0.8

M190 Coach Peel

Joining Process	Joint Efficiency	Normalized Energy	Normalized Stiffness	Peak Load (N)	Energy (J)	Stiffness (N/mm)	Displacement at Peak Load (mm)
Parent Metal	100%	100%	100%	60109	269	38843	5.5
A/SP RSW Starting Schedule (AC)	4%	2%	2%	2318	6	716	4.5
A/SP RSW Starting Schedule (DC)	3%	2%	2%	1941	5	753	3.9
Arc Braze - Plug Joint (10mm hole)	3%	4%	2%	1632	10	802	8.0
Fracture Toughened Adhesive A	4%	0%	27%	2408	0	10367	0.3
Fracture Toughened Adhesive B	3%	0%	21%	1987	1	7999	0.4
Fracture Toughened Adhesive C	3%	0%	26%	1971	0	9921	0.2
GMAW - Arc Spot	3%	2%	2%	1883	5	610	3.8
GMAW - Plug Weld (10mm hole)	5%	4%	2%	2889	11	707	6.7
Hemlok Rivet	6%	5%	1%	3477	13	358	7.0
Laser (15mm lap)	6%	7%	2%	3651	18	601	9.1
Laser (20mm lap)	6%	9%	2%	3730	25	717	10.5
Laser (25mm lap)	6%	11%	2%	3812	30	652	12.7
Laser (staple geometry)	6%	5%	3%	3868	13	1055	6.2
Resistance Spot Weld (AWS D8.1M)	4%	2%	2%	2216	6	720	4.4
RSW/Adhesive A	4%	3%	31%	2497	7	11868	4.4
RSW/Adhesive B	4%	3%	27%	2569	8	10497	4.6
RSW/Adhesive C	4%	3%	28%	2171	7	10819	4.6

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