

Durability of Advanced High Strength Steel Gas Metal Arc Welds

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ABSTRACT

In this study fatigue tests of GMAW (Gas Metal Arc Welding) welded joints were conducted on both 1.6mm body sheet (DQSK-GA, DP590-GA, DP780-GI, and TRIP 780-GI) and 3.4mm frame materials (SAE1008 HR 240MPa, HSLA420 HR, DP600 HR, and uncoated Boron). Further, mixed thickness joints were tested which combined 3.4mm SAE1008 HR with each of the 1.6mm separately – with the exception of DQSK. A number of different joint configurations were tested including single and double lap-shear, start-stop lap shear, butt weld, and perch mount. Great care was taken in this study to ensure that the geometry of the welds was consistent, not only within a given material lay-up, but between all of the specimens of a given type – this effort was made in order to substantially reduce life scatter and provide a better understanding of the role base material plays in the fatigue life of GMAW joints. Fatigue testing was limited to tension-tension loading ($R=P_{min}/P_{max}=0.1$), with limited elevated mean stress testing (DP590 and DP600, all specimen types) conducted at $R=0.3$.

It was determined that, regardless of specimen configuration, base material strength played no role in the fatigue performance of these joints. Further, for all materials and specimen configurations (except perch mount-shear and start-stop specimen configurations) that there was no influence of mean stress on fatigue performance. The thickness of the base metal and the joint had the most significant influence on the fatigue performance of joints. The fatigue performance of mixed thickness joints was either the same or poorer than the

equivalent single material 1.6mm joint. Lastly, attention to consistent weld geometry yielded fatigue life scatter which was significantly reduced over that found in earlier studies.

INTRODUCTION

Enormous and increasing fuel cost pressures in the US are rapidly driving the US automotive industry into radical changes in vehicle aerodynamics, emissions, driveline efficiency and vehicle weight. Vehicle mass reductions are typically accomplished through the substitution of thicker gage lower strength materials such as low carbon and high strength steels with thinner higher strength materials. Advanced High Strength Steels (AHSS) achieve the desired weight reductions at lower cost through improved formability, which results in a thinner section and higher strength than is normally achievable with conventional steels. As with any engineering challenge, weight reduction is an engineering balance between mass reduction, crashworthiness, and durability concerns. In terms of assessing durability, one of the most difficult challenges is assessing bolted and welded structures – these are typically geometrically sensitive areas where fatigue cracks often form. This paper presents a study on one form of joining – Gas Metal Arc Welding (GMAW). GMAW is commonly employed in frames subframes, and unibody construction. It has also found application in tailor welded blanks.

Since vehicle structural integrity critically depends on the structural performance of these welds, the Sheet Steel Fatigue Committee of the Auto-Steel Partnership felt it

was urgent to gain an understanding of welds of Advanced High Strength Steels (AHSS), since these steels are being employed in ever-increasing amounts to improve crashworthiness and reduce vehicle mass. Typical AHSS steels employed by the North American automotive industry include Dual Phase (DP) and martensitic grades (Boron). Transformation Induced Plasticity (TRIP) steels have seen some limited deployment in the North American automotive market. A modicum of published fatigue data on these steels does exist [1-7].

Typical applications have these steels welded to low carbon and high strength low alloy steels (HSLA) members, and so these types of specimen lay-ups were used. However, to determine if a particular AHSS steel truly gives a performance benefit, the Committee also elected to study each particular steel in a like-to-like configuration. Thus, in this study, each of the materials was both welded to itself and to the most likely of either low carbon or HSLA steel (based on current usage). Thus, the AHSS materials in this study included DP600, DP590, DP780, TRIP780, and Boron. The conventional and HSLA steels used were SAE 1008 and HSLA 420. Draw Quality Specially Killed (DQSK) was the single mild steel used in this study. Thinner materials were generally studied with coatings in place, and thicker materials were uncoated.

As for gage, the sheet thickness used in typical applications ranges from less than 1mm (car body sheet) to 8mm (heavy truck frame). In order to reduce the size of the test matrix, only two (typical) thicknesses were selected for study: 1.6mm and 3.4mm. Most specimens were fabricated entirely of one thickness, while a few iterations included specimens of materials of mixed thicknesses.

Recent research has indicated that one of the most critical factors in the fatigue life of welds is the consistency of the cross-sectional geometry of the weld [8]. Traditional weld fatigue curves contain one, two, three, or sometimes more decades of scatter. Much of this scatter in performance is the result of the geometric and processing scatter found in normal weld production (part fit-up, weld gap, variation in feed rates, travel rates, weld angles, etc.). This scatter, which greatly confuses the interpretation of results, intersperses the data sets to such an extent that it is often nearly impossible to discern the effects of the material (and other factors). Because of our interest in determining the relative performance merits of AHSS steels, the committee chose to closely control the weld geometry both within a single lay-up (the particular combination of thicknesses and material types) – hereinafter termed iteration – and across all iterations. Great emphasis was placed on producing the weld cross-sections as consistently as possible so as to reduce the scatter in geometry. Thus it was hoped that all 3.4mm welds were geometrically consistent with each other – it is hoped the same is true for the 1.6mm and 1.6/3.4mm welds. The critical measurements made for weld acceptance were the

vertical and horizontal weld leg lengths, the depth of penetration, and the convexity – toe radius and toe angle were not measured. All these measurements and their variability will be the subject of a later paper. Unfortunately, the great attention to geometry that was paid in weld production for this paper has had the byproduct of causing the fatigue data reported in this paper to likely be somewhat non-conservative for design purposes.

Another large source of scatter within fatigue data are the presence/absence of weld start and stops. These discontinuities are extremely difficult to create consistently and are a frequent source of fatigue crack nucleation in automotive structures. Thus in the interest in determining the effects of material on weld durability performance, the committee elected to eliminate, as much as possible, the presence of starts and stops in the fatigue coupons tested – only one specimen type (the start-stop lap-shear discussed later) had these defects purposely included in the high stress region in order to assess their effects.

The detailed results of fatigue specimen construction and the lessons learned therein will be the subject of another paper.

EXPERIMENTAL PROCEDURE

WELD FABRICATION – The primary goal during fabrication was to create welds which were both sound and geometrically consistent both within iterations and between them. Contrary to standard American Welding Society and automotive manufacturing guidelines on fillet welds (which only specify a minimum leg length of 70% of the base sheet thickness), the fillet welds in this study had both minima and maxima placed upon the horizontal and vertical leg lengths. On thicker gage materials (3.4mm) the horizontal and vertical leg lengths were held to between 0.9x and 1.2x base thickness, while in iterations with thin gage materials (1.6mm) the horizontal leg length was held between 1.8x and 2.0x thickness (vertical was the same at 0.9x–1.2x thickness). Again, this was in an effort to control the variability in the notch factor created by the weld. Further, welds were specified to be convex (weld throat length $\approx$ leg length). No overt effort was made to control toe radius or toe angle. Lap shear specimens constructed of galvanized sheet metal had a weld gap specified to be 10% of the smaller sheet thickness. Butt welds were constrained with the weld to be flush on the specimen back and to stand proud of the front surface by a height between 0.15x–0.25x thickness.

With two exceptions (discussed later), all weld end material within 20mm of the weld stops and starts was discarded in order to further reduce fatigue variability. Specimens were constructed by robot welding long sheets with 70ksi filler wire and water-cooled clamping systems to minimize specimen warpage. Specimens were then waterjet cut to final dimensions.

Reference 9 contains more in-depth discussions of weld production. Appendix A contains one representative weld cross-sectional micrograph from each of the single lap-shear iterations and all of the weld cross-sections examined may be found in reference 10. Table A-1 in the appendix contains the welding parameters used to join the 3.4mm materials, Table A-2, also in the appendix, contains those parameters used to join the 1.6mm materials, and lastly Table A-3 contains the welding parameters used to join the 1.6mm materials to 3.4mm thick SAE1008.

SPECIMEN TYPES AND GEOMETRIES – Five specimen types representing weld geometries commonly found in automotive applications were employed in this study. They were specifically designed such that the weld was centered between the grip areas wherever possible and further that the weld was placed as close as practicable to the specimen centerline to minimize specimen bending. This latter is especially important in specimens fabricated with dissimilar thickness materials.

All materials were tested in the double lap shear specimen configuration, shown in Figure 1. For the sake of illustration, a specimen with dissimilar material thicknesses is shown – in most cases the specimens were symmetric in thickness. The double lap-shear specimen is believed to provide the most consistent fatigue performance, in part because of the additional weld length sampled during testing, but also because the additional load path reduces specimen rotation and distortion during tension-tension axial fatigue testing. All

iterations also included the butt weld specimen as well, as seen in Figure 2. The butt weld was included to determine weld performance under normal loading (no shear or bending as in the lap-shear specimens). The single lap-shear is the industry standard fatigue test specimen and, as such, was tested in most iterations (Figure 3)

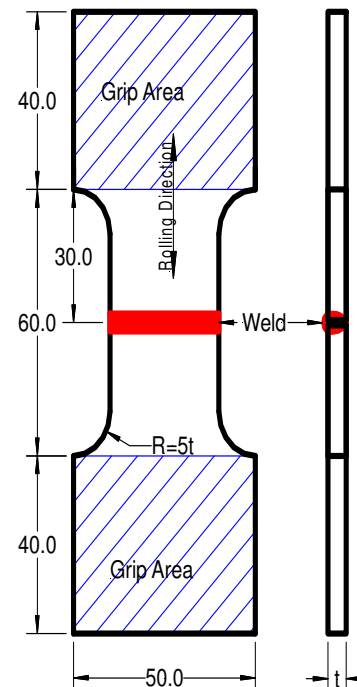


Figure 2. Butt-weld specimen. Dimensions in mm.

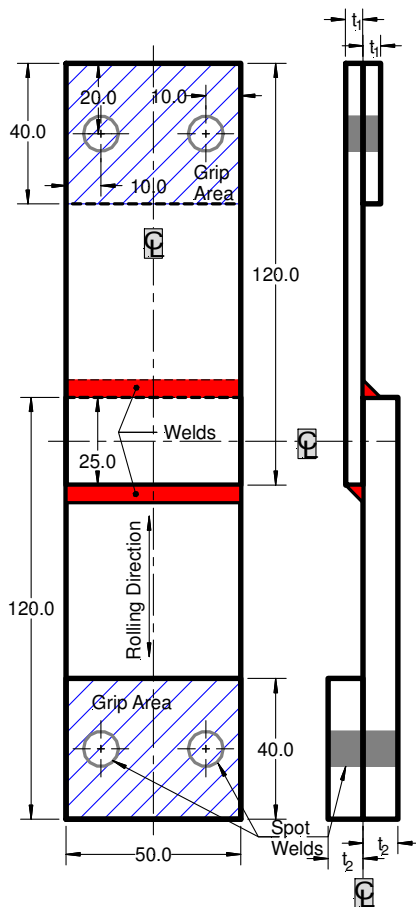


Figure 1. Double lap-shear specimen. Dimen. in mm.

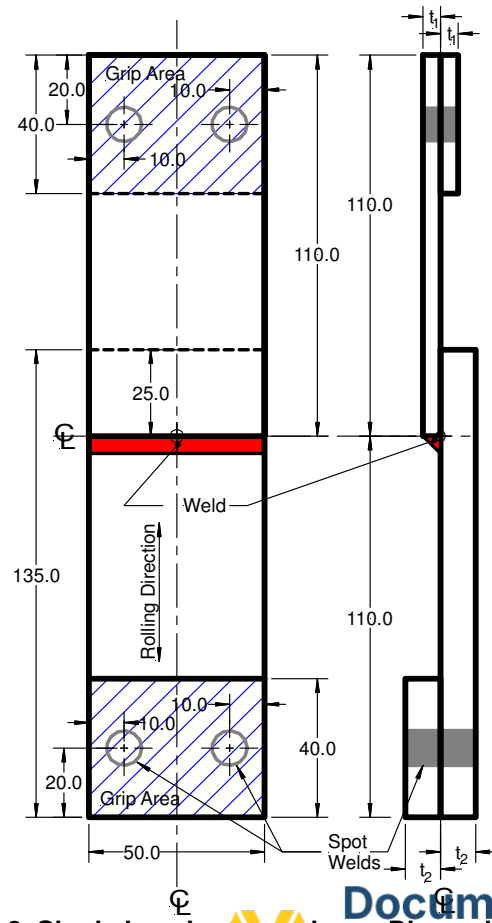


Figure 3. Single lap-shear specimen. Dimen. in mm.

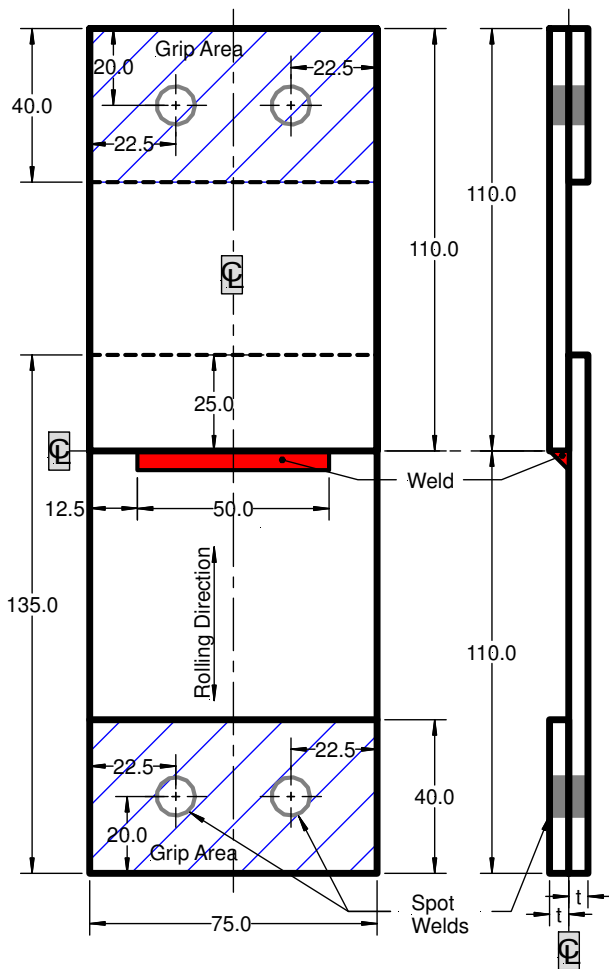


Figure 4. Start-stop specimen. Loading direction coaxial with rolling direction. Dimensions in mm.

The start-stop specimen, Figure 4, was included in a single iteration in order to ferret out the effects of weld-ends on fatigue performance – please note that the specimen width was adjusted to provide the same weld length as found in the single lap-shear specimens, so that suitable comparisons might be made.

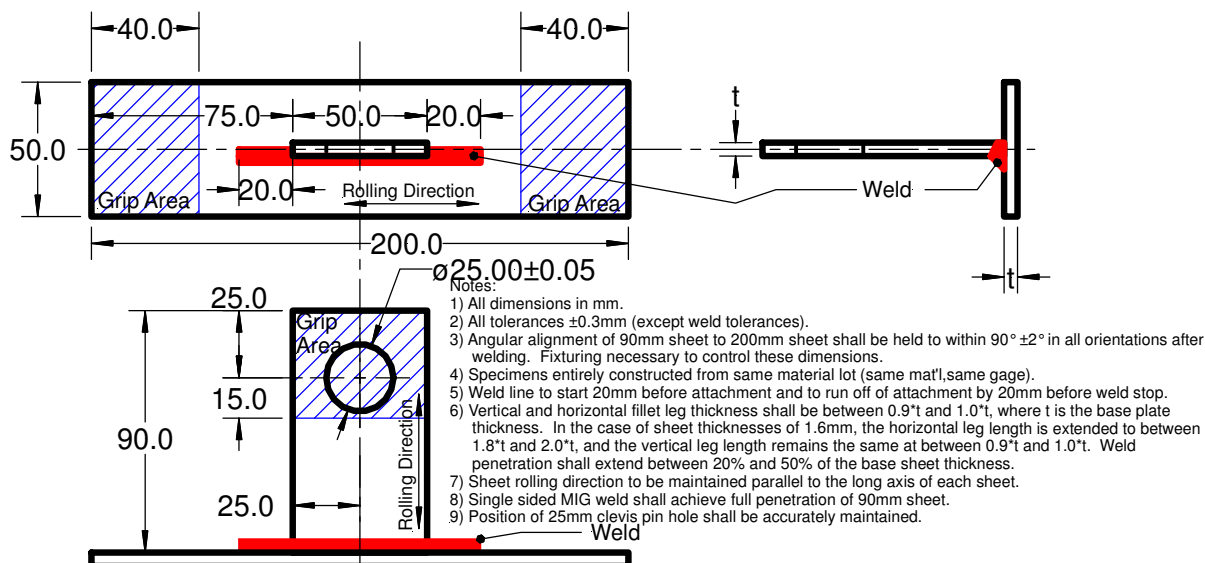


Figure 5. Perch mount specimen. Loading through the central 25mm hole was either in the horizontal (shear) or vertical (normal) directions. Dimensions in mm.

In all of the lap-shear configurations as well as the butt weld specimen the rolling direction of the material was aligned with the fatigue loading direction

Finally, the perch mount specimen (Figure 5) was also tested (two materials only) and was used as a component-like test so that data from the other specimen geometries might be used to estimate perch mount lives and thereby develop and refine life prediction methodologies.

Table 1 shows the materials gages and types of specimens constructed for each iteration. Rows with a single material listed are specimens where the entire specimen consists of that material, and those with two are mixed material lay-ups.

TENSILE AND FATIGUE TESTS – Tensile tests were conducted to determine the peak load carrying capacity (P_{max}) of the welded joints. At least two specimens were used for tensile tests for each iteration/geometry, and tensile tests were conducted at a crosshead rate of 2.54 mm/min.

All fatigue tests were conducted according to ASTM E466-07. Load controlled fatigue testing was conducted on all iterations and geometries at $R=0.1$ (P_{min}/P_{max}). Two selected iterations (1.6mm DP590GA and 3.4mm DP600 HR) were also tested at $R=0.3$ to determine the influence of mean stress on weld fatigue. Each fatigue curve comprised at least three (3) different load levels and at least three valid repetitions within each of those load levels. Specimen failure was defined as full separation. Fatigue test were usually suspended after a *runout* life of 5×10^6 cycles. However, if the compliance change for a given specimen was greater than 20% by the time the runout life was reached, the test was continued until specimen failure.

Table 1. Materials, gages and specimens types.

Material*	Gage (mm)	Single Lap Shear	Double Lap Shear	Butt Weld	Perch Mount	Start-Stop
SAE 1008 HR, $S_y=240$ MPa	3.40	X	X	X		
HSLA 420 HR	3.40	X	X	X	X	
DP600 HR	3.40	X	X	X	X	X
Boron, uncoated	3.40	X	X	X		
DQSK GA	1.60		X	X		
DP590 GA	1.60	X	X	X		
DP 780 GI	1.60		X	X		
TRIP 780 GI	1.60		X	X		
DP590GA to SAE1008 HR	1.60 to 3.40		X	X		
DP600HR to SAE1008	3.40		X	X		
TRIP780 GI to SAE1008	1.60 to 3.40		X	X		
DP780 GI to SAE1008 HR	1.60 to 3.40		X	X		

*An iteration constructed from a single (same-to-same) material combination has the material mentioned but once. Iterations constructed from different materials have both listed, and the second listed material is the base to which the first is welded. Shaded iterations (DP590GA and DP600HR) had additional R=0.3 testing performed.

Special care was given to ensure that specimen mounting was consistent between tests – specifically that the weld was centered between the grips and that the exposed length was identical for each specimen type. These steps were taken because of the adverse effect on the levels of bending and tensile stress in the weld (and hence fatigue life) that these misalignments can cause.

All test machines used were aligned according to ASTM E1012-05 and calibrated according to ASTM E467 - 98a(2004). Cycle number, maximum/minimum load and displacement were recorded for cycles in logarithmic increments out to 50,000 cycles, and thereafter for every 50,000 cycles until specimen failure.

RESULTS AND DISCUSSION

RELATIVE QUALITY OF WELD CONSTRUCTION – detailed weld geometry measurements were made on each of the fatigue specimens tested, and these data will be correlated more directly with fatigue performance in a later paper. However, non-destructive visual observations of weld quality were made for the various specimens, because it has a direct impact on fatigue performance and scatter.

The most consistent welds and those which had a very clean appearance were the monolithic (same thickness, same material) single lap-shear specimens and the perch mount specimens. Monolithic double lap and 3.4mm monolithic butt welds were also quite good. However, the single worst welds in terms of defects were the 1.6mm/3.4mm butt weld joints closely followed by 1.6mm monolithic butt welded joints. Almost every one of the 1.6mm to 3.4mm mixed thickness double lap joints were pocked with divots and some porosity along their length, and several had intermittent lack-of-fusion zones along the weld length where the 3.4mm material was welded to the 1.6mm base – these flaws almost certainly lessen fatigue performance. The worst of these were set aside, and only a couple of these questionable mixed thickness double-lap specimens were used in the testing.

TENSILE TESTS ON WELDED JOINTS – Figure 6 shows the peak tensile load for all tensile shear tests on welds involving 3.4mm materials. On the left side of the graphs are all 3.4mm to 3.4mm welds of materials welded to themselves, and on the right are dissimilar material welds – the first is a 3.4mm to 3.4mm weld, and the remaining three are all 1.6mm to 3.4mm welds. The graph includes tests on all 3.4mm single lap-shear, double lap-shear and start-stop lap-shear specimens.

The comparison of single and double lap joints shows that they perform similarly for low and medium strength materials such as SAE1008 and HSLA420. However, for boron steel, there is a significant performance improvement likely because this joint is more balanced and thus is better for notch sensitive materials such as boron steel. The start-stop weld performance (DP600HR) is only slightly lower than that of the single lap shear and is about ¾ of the double-lap shear results.

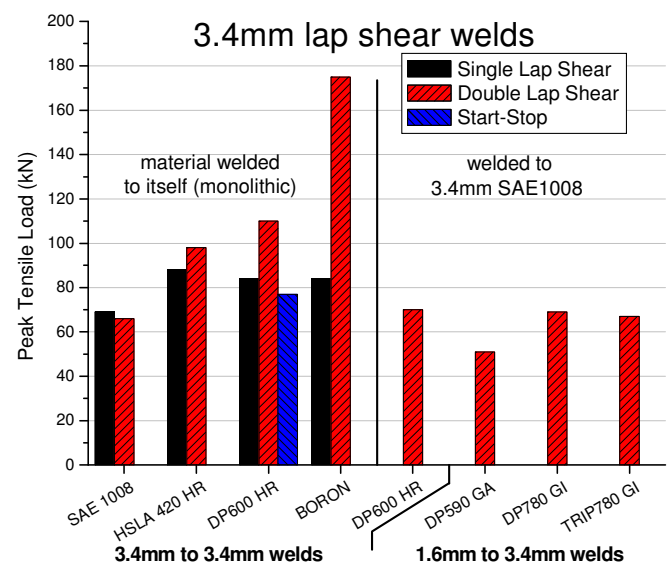


Figure 6. 3.4mm and 1.6-3.4mm tensile testing results for single/double and stop-start lap-shear, specimens..



Documents

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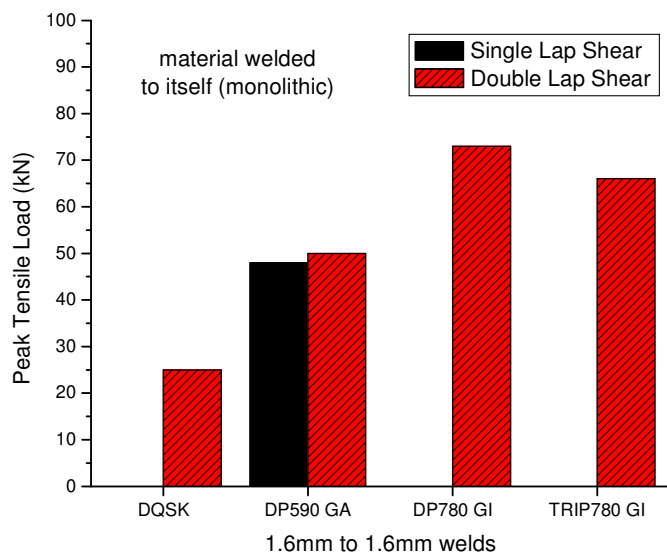


Figure 7. Tensile testing results on all 1.6mm to 1.6mm welds including single and double lap shear.

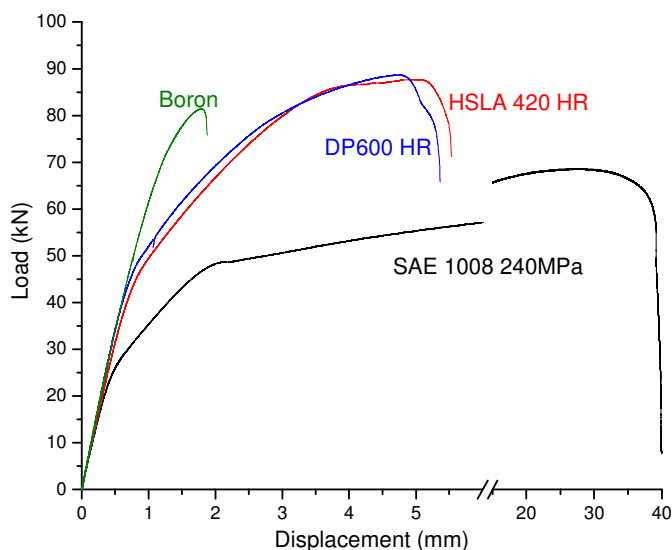


Figure 8. Load-displacement curves for 3.4mm single lap shear specimens.

Figure 7 shows the results from 1.6mm materials welded to themselves. The results are fairly consistent in that the joint strength scales with base metal strength, although the DQSK fractured in the parent metal.

Unsurprisingly, the strength of double lap shear joints constructed of DP600HR welded to SAE1008 HR is roughly similar to monolithic SAE1008 HR double lap shear joints. More interesting is the result that the high strength 1.6mm materials welded to 3.4mm SAE1008 HR yield joint strengths similar to that of the SAE1008 HR welded to itself.

Example load versus displacement curves for single lap-shear specimens are shown in Figure 8 to show the relative ductility of each material. Boron steel showed very limited ductility; DP600 HR and HSLA420 HR had reasonable ductility; and SAE1008 HR showed considerable ductility. Figure 9 shows example load-displacement curves for double lap-shear specimens of the 1.6mm materials as well as the 1.6mm materials

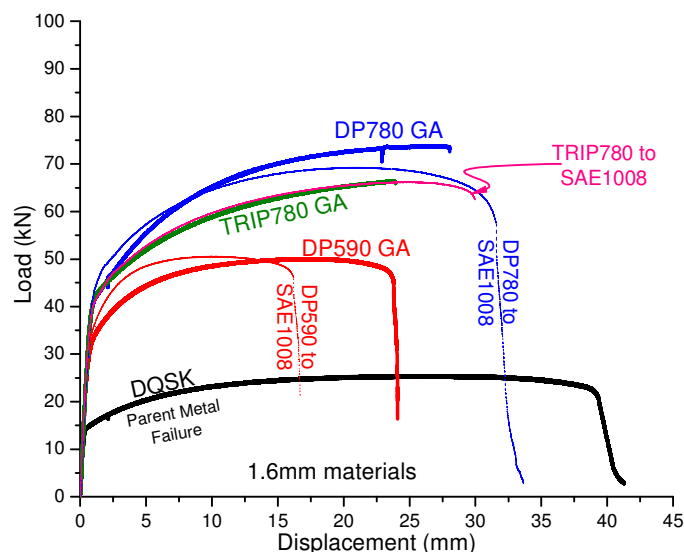


Figure 9. Load vs. displacement curves for double lap-shear specimens constructed of 1.6mm materials and 1.6mm materials welded to 3.4mm SAE1008.

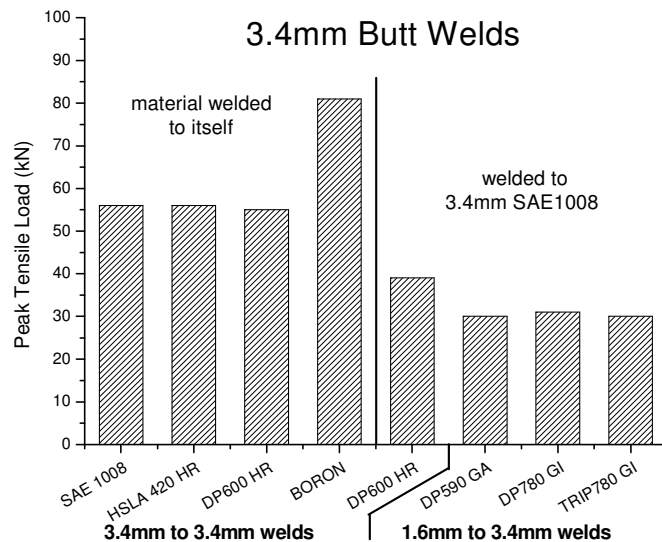


Figure 10. Tensile test results from all 3.4mm butt welds, including 1.6m to 3.4mm.

welded to 3.4mm SAE 1008. All of these specimens show considerable ductility, and the addition of SAE1008 only seems to improve the ductility of the joint, with the exception of DP590GA – in this particular case the DP590 base metal is probably of lower load capacity than the SAE1008 and thus limits the overall performance of the joint.

Peak tensile loads from 3.4mm butt weld specimen can be found in Figure 10. The performance of the butt weld joints is similar for all 3.4mm to 3.4mm butt welds, except for Boron steel, which was about 50% higher. Unlike in the double lap shear results, the DP600 HR welded to SAE1008 (3.4mm to 3.4mm) was a somewhat weaker joint than the monolithic SAE1008 joint.