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Fatigue Properties of Stainless Steel Lap Joints.

Spot welded, adhesive bonded, weldbonded, laser welded and clinched joints of stainless steel sheets-a review of their fatigue properties.

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ABSTRACT

The type of joints covered are i) spot welded stainless to stainless and to galvanised carbon steel, ii) adhesive bonded stainless to stainless, iii) weld bonded stainless to stainless, iv) laser welded stainless to stainless and to galvanised carbon steel, v) clinched stainless to stainless steel.

The materials studied are AISI 301 and 304 stainless steel and high strength duplex 2101, 2304, 2205 and 2507 stainless steel. The thickness range is 0.7 – 4 mm. Fatigue properties in terms of Wöhler curves and Fatigue strength at $2*10^6$ cycles are compared between the different joining methods using load transfer capacity per unit length of the joints.

Fatigue strength is shown to be independent of matrix strength for spot welded joints. Spot welded, laser welded and clinched joints show similar fatigue properties for 1mm sheet joints. Adhesive bonded joints are five-fold stronger and the weld bonded joints show considerable scatter with a lower bound fatigue strength between spot welded and adhesive bonded joints.

INTRODUCTION

Structural applications represent one of the fastest growing segments for stainless steel. In the US market some 20 percent of all stainless steel is estimated to be used in this market sector. A good example of a growing sub-segment is the transportation, e.g. in busses and trains.

It is not only the corrosion resistance of stainless steels which is of interest. To further increase the penetration of this market we need to develop our understanding of the mechanical properties of stainless steel and stainless steel structural elements. This means among other things a need to develop joining techniques suitable for these applications, to establish the behaviour of structural elements under static and dynamic loads, to develop design guides etc.

In the basic mill-annealed condition, stainless steel grades are available with yield strengths ranging from 260 to 620 MPa. In the temper rolled (cold rolled) condition, grades are available with yield strengths from 350 to 1500 MPa. The high strengths available will lead to lighter, more slender structures based on thin sheet panels, shells and members in general.

The thin sections will call for new techniques for fabrication and joining of members. Traditional butt welding techniques will be used but the thin section will make it feasible to join with other methods using overlap joints.

In this report a number of overlap joining methods is considered with special focus on the fatigue properties of such joints. Most of the results presented are results from a series of PhD studies financed by Outokumpu Stainless Research Foundations in a long term program to increase the knowledge of thin sheet joining techniques.

SINGLE OVERLAP JOINT

ROTATION OF OVERLAP JOINTS

The eccentricity of the load path, figure 1, results in a rotation of the joint during loading. This will result in a tensile load (opening Mode I) in combination with the shear load. This effect has been demonstrated a number of times over the last decades, mostly using FEM techniques, figure 2 (1).

Measurements and a mechanical model of joint rotation have been reported recently (2). For normal combinations of loads and sheet thickness the rotation rarely exceeds three degrees.

The limiting nominal stress for which an elastic model holds is set by the onset of local plasticity. In the lap joint this happens first at the inner fiber, i.e. the stress at the surface where the sheets join is first to reach the yield value.

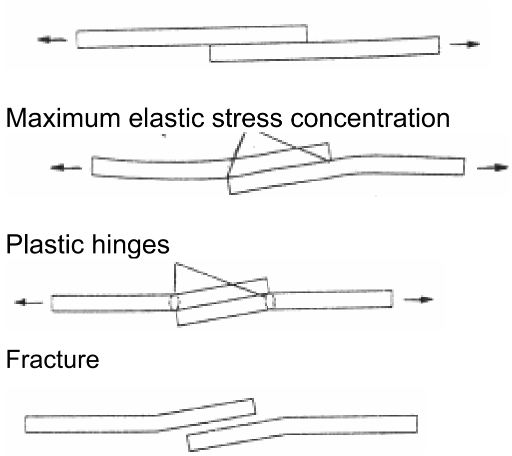


Figure 1 Deformation of lap joint during loading.

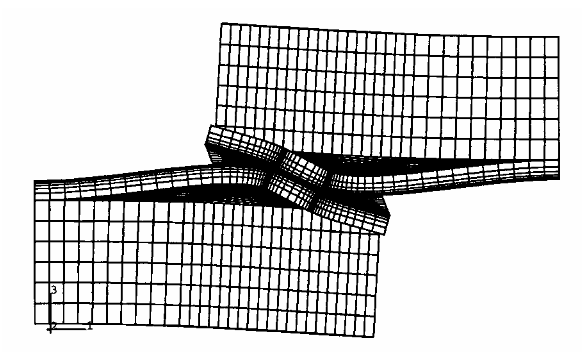


Figure 2 FEM analysis of spot-welded joint showing rotation of joint (1).

The stress distribution in the sheet due to the shear load moment is found from

$$\int \sigma(x) dx = Q$$

and

$$\int \sigma(x) \cdot x \cdot dx = 0$$

integrated from 0 to t,

to be $$\sigma = \frac{2Q}{t}\left(2 - 3\frac{x}{t}\right),$$

This results in a maximum stress at the inner surface

$$\sigma = \frac{4Q}{t} , \qquad \text{Equ.(1)}$$

This simple, two-dimensional calculation of maximum stress can only be used for continuous joints such as those laser welded or adhesively bonded, but will underestimate the stress close to a spot weld, especially for thicker sheets.

LAP JOINT LOAD TRANSFER CAPABILITY

In most engineering research reports the tensile and fatigue strengths are given in terms of net section stress. This is the case also for continuous butt joints. For spot welded joints there seems be no general rule. Some reports give total load and define the number of spot welds, others report the strength as the net section stress of the specimen tested and still others have reported strength as the corresponding shear stress on the spot weld.
To be able to compare the properties of different joining techniques the strength of the joints will be given both as load range and as the "line load", Q, i.e. the load divided by the width of the joint. Dividing the line load with the thickness then gives the net section stress.
For discontinuous joining techniques (e.g. spot welding, riveting, clinching) the width of the joint has to be defined for each technique. In the following the optimal distance between the closest two spot welds, the "pitch", will be calculated by

$$e = (14 \cdot t_2 + 3) \cdot \sqrt[3]{t_1 / t_2} \quad \text{where } t_1 > t_2 \qquad \text{Equ.(2)}$$

Thus for $t = t_1 = t_2$

$$e = 14\,t + 3 \qquad \text{Equ.(2b)}$$

The optimum pitch is then 17, 24, 45 and 59 for thickness 1, 1.5, 3 and 4 mm respectively.

For a spot welded joint the line load is thus calculated as load per nugget divided by the pitch calculated by the equation above.
Nugget size has in all reports followed normally recommended $d = 5 \times \sqrt{t}$, with d and t in mm.

MATERIALS

The nominal chemical compositions of the materials considered in this review are given in Table I.

SPOT WELDED JOINTS – STAINLESS TO STAINLESS

MEDIUM STRENGTH AISI 304 – SINGLE SPOT SPECIMENS

Linder and co-workers (1,3,4) have studied the spot welded joint with particular reference to fatigue behaviour. A separate study by Marples (11) is also reported in this section.
Three different joint configurations (test specimen types) have been studied, figure 3.

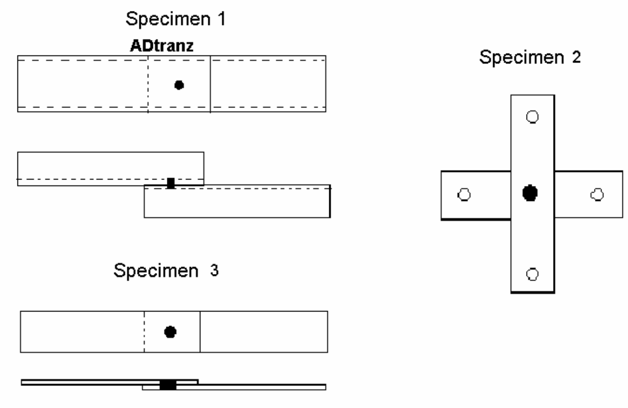


Figure 3 Lap joint specimens used to study spot welding, adhesive bonding and weldbonding.

Specimen type 3 is the standard single overlap joint. To increase the stiffness and reduce transverse forces specimen type 1 was designed with stiffening flanges. This specimen type is sometimes called the “Box” specimen. For these two types the load transfer is basically shear but with an increasing transverse force for specimen type 3. To investigate the strength in pure tension transverse the sheets specimen type 2 was used.
The materials tested were the austenitic grade AISI 304CS in the pre-strained condition and standard, annealed AISI 304. Mechanical properties are given in Table II
Fatigue testing was performed with the specimen types shown with sheet thickness 1.0, 1.5, 3 and 4 mm. The results are given in Table III and as Wöhler type curves in figure 4.
The fatigue limit for 304CS expressed in load range varied between 0.21 kN for specimens of type 2, thickness 1.5 mm to 4.16 kN for type 1, of thickness 4 mm.

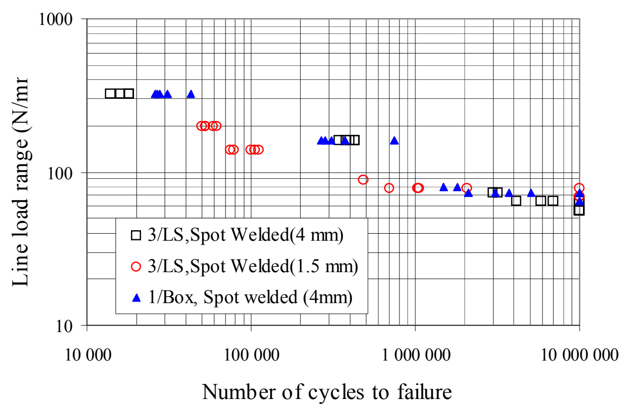


Figure 4 Fatigue properties of spot welded AISI 304CS.

<u>Fracture mechanics approach to the analysis of fatigue properties of spot welded joints.</u>

The fatigue properties of spot welded joints of stainless steel sheets range from 6 to 70 MPa (Table III) compared with the bulk fatigue properties of 250 to 400 MPa. This poor fatigue strength demonstrates the importance of a reliable design tool for spot welded joints. Linder and co-authors (1) suggested a fracture mechanics approach for the analysis of the results. The basis for this was that the two sheets create a crack ending at the weld nugget. Stress intensities around the weld nugget for tensile and shear loads (Mode I-III) were calculated for different angels ϕ from the loading axis, in order to find the maximum stress intensity and its location along the spot weld nugget. The result from this calculation is presented in the form of an effective stress intensity factor, K_{eff}, defined as:

$$K_{eff} = (K_I^{\,2} + K_{II}^{\,2} + K_{III}^{\,2}/(1-\nu))^{½} \qquad \text{Equ.(3)}$$

For specimen types 1 and 3 the maximum effective stress intensity factor, K_{eff}^{max} , was found exclusively along the loading axis where fatigue cracks were also observed to initiate. For peel loaded specimens (type 2), K_{eff}^{max} was found to be almost constant along the nugget periphery. The variation of the stress intensity parameters is shown in figure 5 for type 1 specimens.

K_{eff}^{max}/P values for the three specimen types and different sheet thicknesses are given in Table IV.

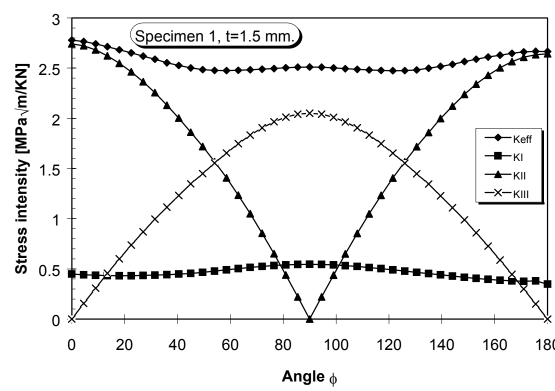


Figure 5 Variation of stress intensity factor for type 1 specimen.

All load ranges for the failed specimens were recalculated using K_{eff}^{max}/P in Table IV. The stress intensity ranges, $\Delta K = \Delta P * (K_{eff}^{max}/P)$, versus number of cycles to failure for all specimen types, sheet thickness and steel grades are shown in figure 6.
In figure 7 the two materials tested are separated. The results show that lap joints of the duplex grade (SAF 2304) have slightly higher fatigue strength than the austenitic 304CS, both at the same tensile strength level.

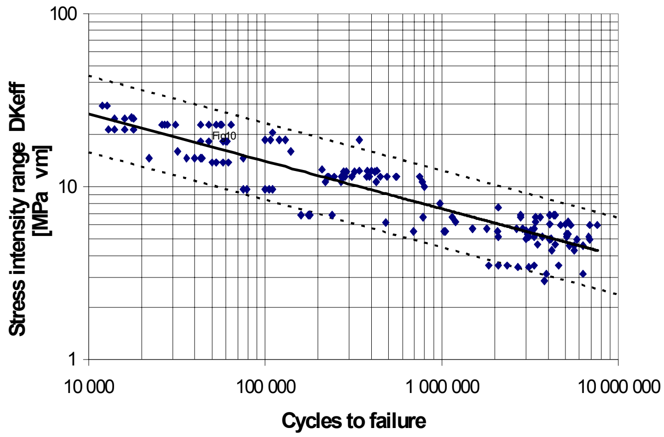


Figure 6 Stress intensity ranges versus number of cycles to failure for all specimen types, sheet thickness and steel grades. 95% confidence limits are shown.

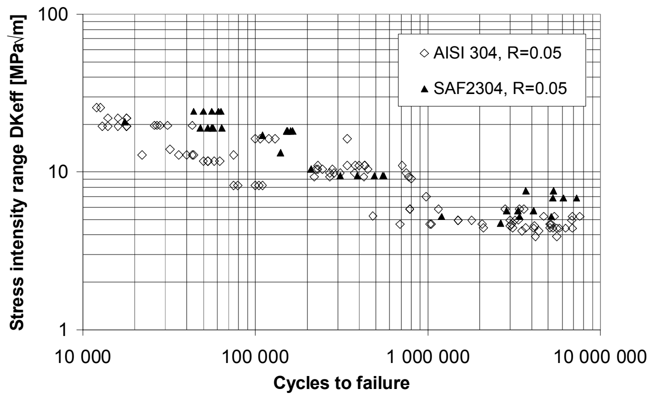


Figure 7 Stress intensity ranges versus number of cycles to failure for specimen types 1 and 2, all sheet thickness and with steel grades separated.

HIGH-STRENGTH AISI 301

Nord (5) has tested spot and projection welded 1.5 mm temper rolled AISI 301 using a 46 mm wide type 3 specimen. Yield and tensile strengths were 1072 and 1391 MPa respectively.
The number of specimens tested for each series of spot welded joints was insufficient for a calculation of confidence limits but, brought together as in figure 8, the fatigue strength at $2*10^6$ cycles can be estimated to be 1.68 kN or 70 N/mm, assuming a 24 mm pitch. The uncertainty is estimated as $\pm$10 N/mm. Nugget size was 6.4 mm. For a smaller nugget size, 5.3 mm, the fatigue strength is reduced but the test series was too small to ensure a significant difference. These results are similar to those reported for the medium-strength AISI 304 above.
The weld is localised to a contact area normally with a number of projections designed to suit thickness and strength requirements. With a large electrode covering all projections they can be welded in one operation.

The fatigue results given in figure 10 indicate similar values as for standard spot welding, i.e. 70 $\pm$ 10 N/mm. The load data have been transferred to a line load range assuming a pitch of 20 mm.
Adhesive tape increases the fatigue strength from 70 to 120 N/mm or with 70% for the projecting welded joints.

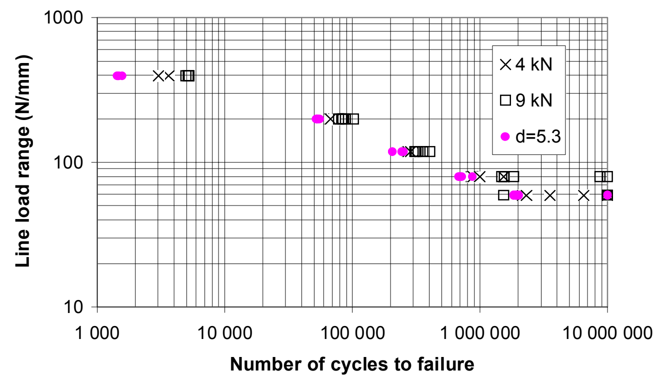


Figure 8 Fatigue properties of spot-welded temper rolled AISI 301. The two series with different clamping forces both had 6.4 mm diameter nuggets.

Nord also studied projection welded joints. On one of the sheets a projection, figure 9, was manufactured

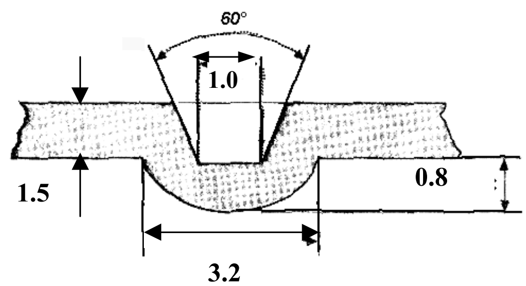


Figure 9 The projection and its dimension in mm.

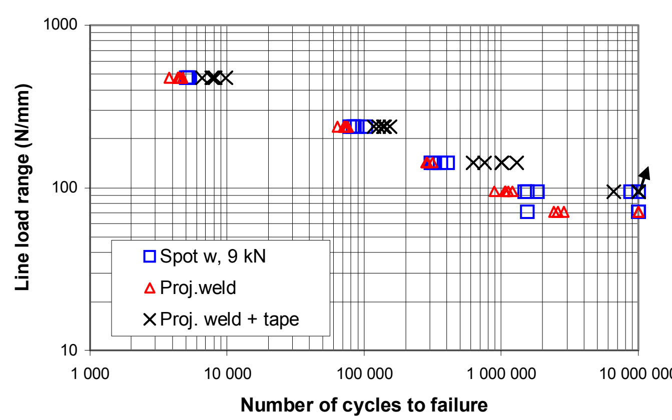


Figure 10 Fatigue results from spot and projection welded single spot welded joints of temper rolled AISI 301. 6.8 mm nugget diameter.

Forsman and co-workers (6) have tested 0.8 mm temper rolled AISI 301 (1153 MPa tensile strength) using both spot welding and projection welding. The latter method was also used together with a 0.13 mm thick by 43 mm wide (3M VHB) adhesive transfer tape. The specimen used was 60 mm wide, type 3 with a 43 mm over lap and a 100 mm grip distance. A limited number of specimens were tested at two load levels for each joint type. The results are illustrated in figure 11. The authors states that the different fatigue lives for the projection and spot welded joints can be explained entirely by the different nugget sizes, 3.5 and 2.6 mm respectively.

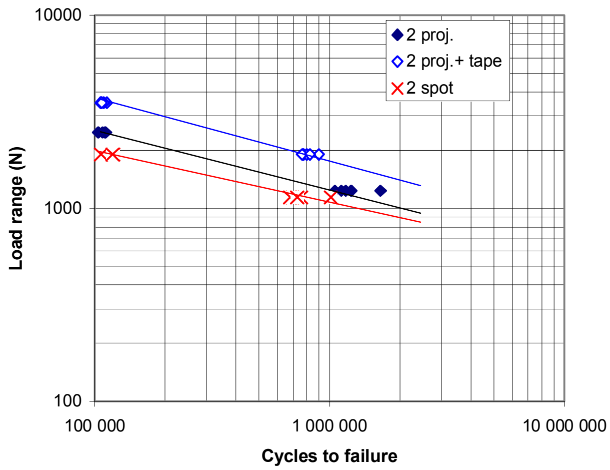


Figure 11 Fatigue properties for spot welded and projection welded, with and without adhesive tape, 0.8 mm temper rolled AISI 301. The loads refer to a specimen with two nuggets.

As a result of using the undersized nuggets, the estimated fatigue strength at $2*10^6$ cycles is substantially lower than those values given above for AISI 301 and 304. Using a pitch of 16 mm the estimated line load range at $2*10^6$ cycles is 28 N/mm for the spot welded joints and 37 N/mm for projection welded joints.
The introduction of a 43 mm wide adhesive tape increases the estimated fatigue strength by 18 % to 44 N/mm. This increase is explained by the stiffening effect of the tape, reducing the rotation of the joint during loading.

MEDIUM STRENGTH AISI 304 AND 301 – MULTIPLE SPOT SPECIMENS

Ueda and Kawataka (7) tested single row, multiple spot joints of 1.5 mm thick AISI 301. The fatigue testing was done on a 120 mm wide specimen with 35 mm over lap and 192 mm grip distance. Over the width 2, 3, 4, 6 and 12 nuggets with 7 mm diameter were welded. This resulted in pitch distances of 60, 40, 30, 20 and 10 mm. The results are shown in figure 12 below.
Since only 4-6 specimens were tested for each specimen configuration the estimated uncertainty for each configuration is high. High stress data (3 kN/nugget) indicate an increasing life for fewer nuggets (larger pitch). At $2*10^6$ cycles life the curves converge to about 1.8 ± 0.1 kN/nugget for all except the specimens with 12 nuggets. This fatigue limit transferred to a line load with optimum pitch of 24 mm is 75 ± 4 N/mm.
These results justify the recalculation used in this review of fatigue data for one-nugget specimens with standard 40-50 mm width to line load using the optimum pitch.

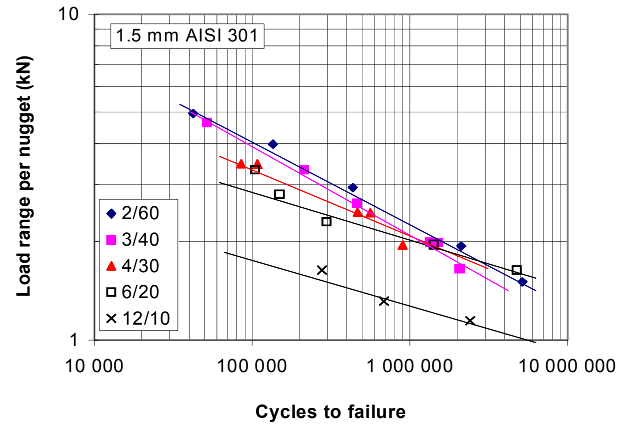


Figure 12 Fatigue results for multiple spot welded joints of 1.5 mm AISI 301 at 417 MPa yield strength level. Code: No of nuggets /Pitch. Recalculated from Ref.(7).

Söderlund (8) tested 4 mm thick AISI 304 in both the annealed and cold stretched (CS) condition. Yield strengths were 288 and 420 MPa respectively. In a 150 mm wide specimen with 100 mm over lap four spot welds were placed in a quadratic fashion with a 75 mm pitch and a row distance of 60 mm. Nugget size was 12 mm. The fatigue strength at $2*10^6$ cycles was estimated to be 3.16 kN/nugget. The fatigue results are shown in figure 13.

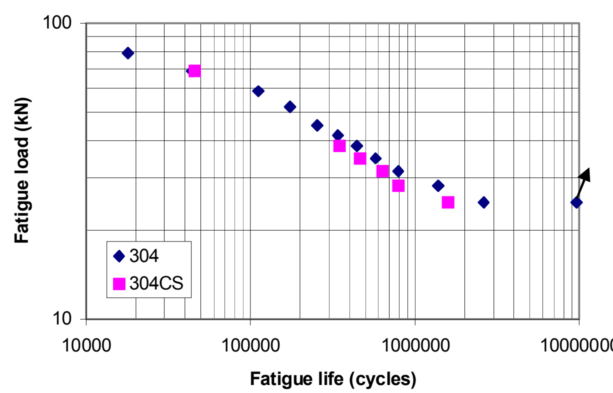


Figure 13 Fatigue results for multi-spot 4 mm AISI 304 in annealed and cold stretch condition (304CS). Each specimen has 4 nuggets.

The cold stretched material was approximately 4% thinner and this, according to Söderlund may explain the small difference between the two conditions. With a thickness correction of the results for the 304CS material and their transfer to line load range with an optimum pitch of 59 mm, the results are as in figure 14 with a $2*10^6$ cycles fatigue strength of 107 N/mm. This may be compared with the results of Linder (5) with a fatigue limit of 60-70 N/mm. The larger nugget size and the increased stiffness due to the two rows are the natural causes for this difference.

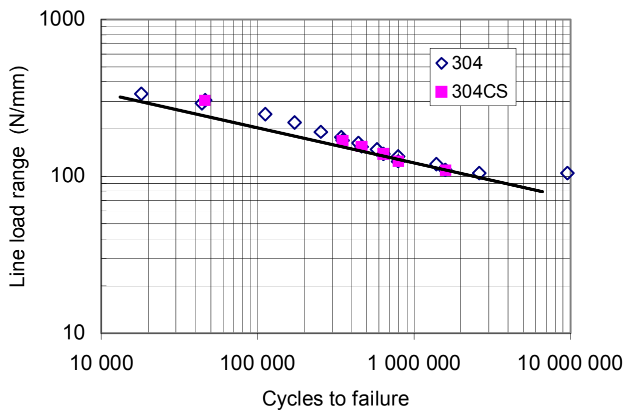


Figure 14 Fatigue properties for 4 mm AISI 304 at two strength levels. The joints consist of two rows of spot welds 60 mm apart.

DUPLEX STAINLESS STEELS

Wray (9) and Linder (3, 4) have studied the fatigue performance of spot welded duplex stainless steels. In Linder's case the spot welding parameters were the same as for the austenitic stainless steels reported above. Wray attempted to optimise the welding parameters (time, current and pressure) to achieve the best micro- and macrostructures. Welding current was varied between 4.7 to 5 kA with 15 cycles for 2101 and SAF 2304, 20 cycles for 2205 and 25 cycles for SAF 2507. The electrode force was 3.25 kN. The nugget diameter was 4.5 to 4.9 mm.
The mechanical properties of the duplex steels investigated are given in Table V.

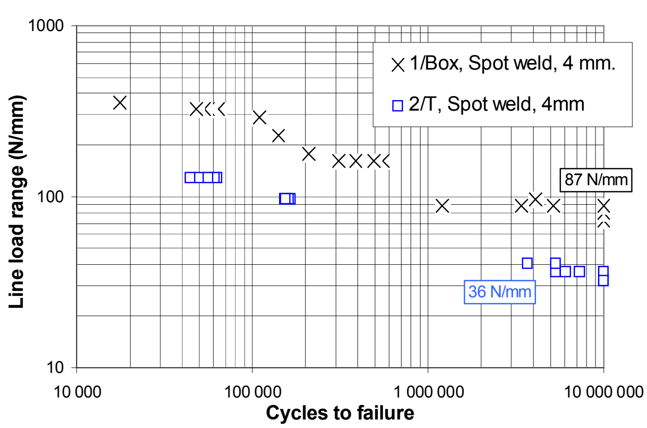


Figure 15 Fatigue results for 4 mm, spot welded SAF 2304 duplex stainless steel. 2/T indicates transverse loaded specimen type 2. All at 10^7 were runouts.

Linder tested box-type 1 specimen and Wray used the simple type 3 lap joint specimen. For both, an unclamped length of 100 mm was used. For the fatigue strength evaluation Linder used a break-off life of 10^7 cycles but Wray used $2*10^6$ cycles.
Their results are given in Table VI and figures 15 and 16

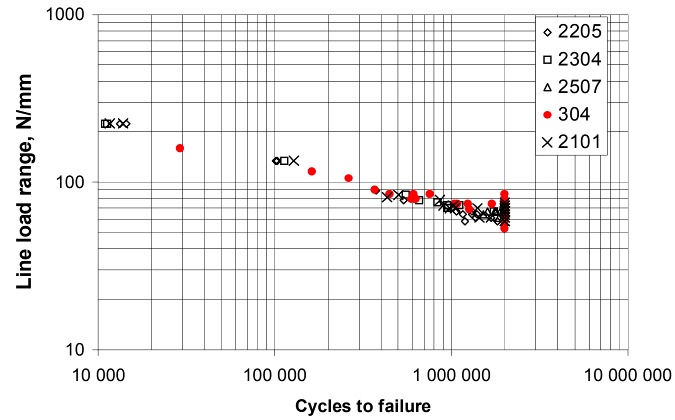


Figure 16 Line load range versus cycles to failure graph for resistance spot welded 1mm thick duplex stainless steels compared to 1mm, AISI 304, all in annealed condition. All at $2*10^6$ were runouts.

Joints with 1 mm sheets have a fatigue strength at $2*10^6$ cycles of 70 N/mm. The 4 mm thick material tested with the stiffer type 1 specimen show consistent higher fatigue strength (87 N/mm). However, considering the reported confidence limits the difference is not statistically significant.

EFFECT OF CORROSIVE ENVIRONMENT

The effect of a corrosive (3% NaCl aqueous) environment on the fatigue properties of spot welded AISI 304 and duplex SAF 2304 stainless steel is reported by Linder and Melander (10). The study was made on 4 mm sheet material using specimen type 1 at ambient temperature and 50 Hz. In the fatigue testing the run-out was set at 10^7 cycles and the testing time was thus up to 60 hours. Results are shown in figure 17 and 18 and table VII.

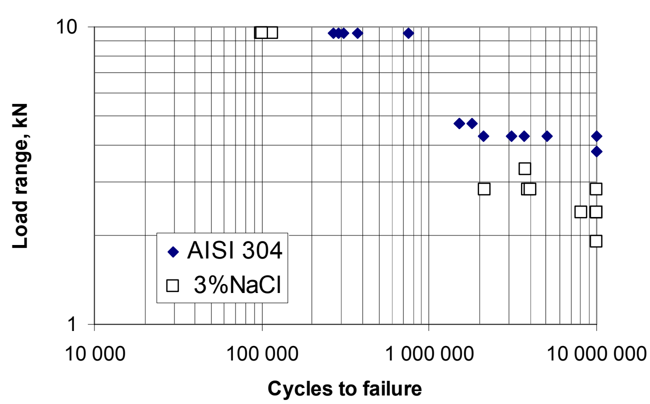


Figure 17 Effect of 3% NaCl environment on fatigue properties of spot welded AISI 304 stainless steel. 10^7 cycles life are all run-outs.

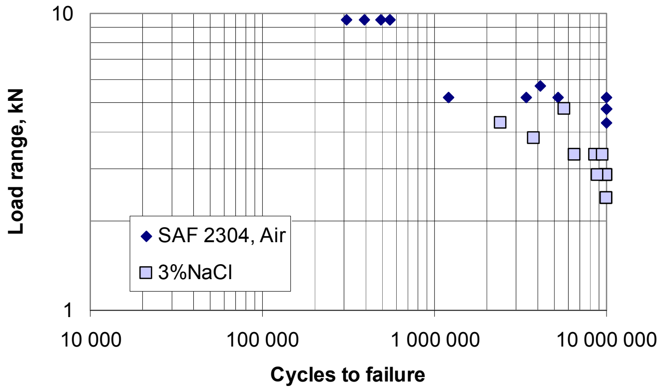


Figure 18 Effect of 3% NaCl environment on fatigue properties of spot welded duplex SAF 2304 stainless steel. 10^7 cycles life are all run-outs.

The fatigue strength at 10^7 cycles is reduced by 35 to 40 % due to the very aggressive 3% sodium chloride environment. Pre-exposure up to 2000 hours did not further reduce the fatigue strength

SPOT WELDED JOINTS – STAINLESS TO GALVANISED CARBON STEEL

Marples (11) have studied spot welding of AISI 304 stainless steel to a galvanised 0.08 %C mild steel, V1437 (GS for short). Details of the materials are given in Table VIII.
Sheets thicknesses were chosen to give approximately equal strength.
The sheets were welded with a 2.8 kN electrode force, 7.8 kA current for 40cycles at 50Hz.
Fatigue testing was done at 10 Hz with R = 0.1 and with an unclamped specimen length of 120 mm.
Although there is Zn and Ni diffusion close to the weld there was no evidence of liquid metal embrittlement.

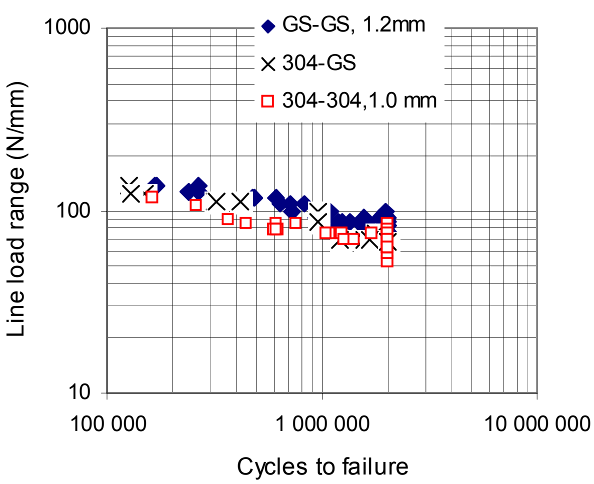


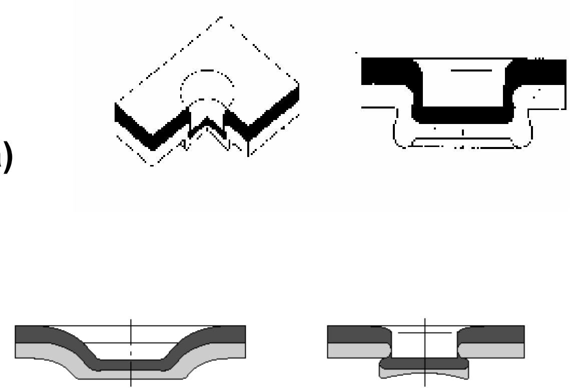
Figure 19 Fatigue of dissimilar metals spot welds. AISI 304 to galvanised mild steel.

The 304-304 and the 304-GS joints show almost identical fatigue strengths at $2*10^6$ cycles with 74 and 73 N/mm (1.20 and 1.24 kN) respectively. Note that the pitch is calculated to be higher for the mixed joint (18 mm) than for the stainless to stainless joint (17). The carbon steel joint gave a fatigue strength of 84 N/mm or 1.66 kN (20 mm pitch)

CLINCHING

Within the automotive sector mechanical joining using a clinching technique is increasing. In figure 20 a perspective view of a typical clinch element is shown.
So far most of the experience is with soft, mild steel and aluminium alloys. The response given by stainless steels with their characteristic higher strength, strong deformation hardening and high ductility, have to be investigated to establish the limiting parameters for clinching.

a)



b)

Figure 20 Perspective view and cross section of a) Round clinch element and b) Rectangular, partly sheared clinch (12).

The joint tensile strengths of a clinch in different 1 mm sheet materials are shown in figure 21 together with the tensile strengths of the materials. This indicates a definite benefit for stainless steel with its higher strength at equal or higher ductility.

Fatigue properties of clinched stainless steel joints have been reported by Jacobsen (13). Non-penetrating, round clinches as in figure 20a, with a 5 mm punch was used on 1.0 mm thick type AISI 304 sheet. Since clinching introduces large plastic deformations in the clinched area, both a slightly unstable grade CrNi 18 10 and the more stable grade CrNi 18 12 were tested. The Yield strength, $R_{p0.2.}$ was 295 and 239 MPa respectively. A type 3 specimen with 50 mm width and 25 mm overlap was used. Grip distance is believed to be 175 mm. Results are given in figure 21 estimating the fatigue strength at $2*10^6$ cycles to be 2.2 kN for CrNi 18 10 and 1.6 kN for CrNi 18 12. The local strength in the clinch seems to affect the fatigue strength.

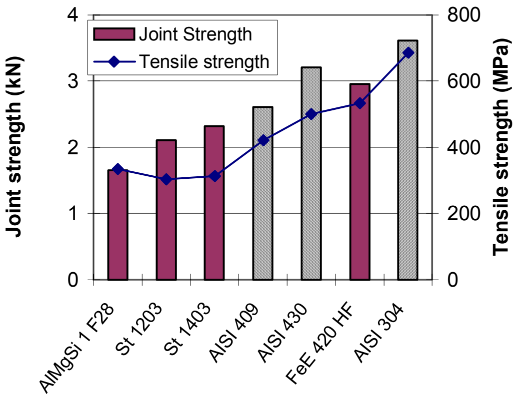


Figure 21 Clinch joint strength and tensile strength for different 1 mm sheet materials (12).

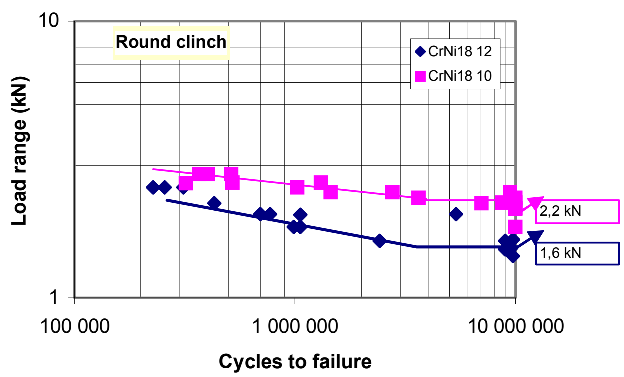


Figure 21 S-N curves for 1 mm clinched lap shear joints. From Ref.(13).

P.Sjöström (14) has tested three standard stainless steels with different stability against strain induced martensitic transformation; AISI 301, 304 and 316 with $R_{p0.2} \approx 300$ MPa. AISI 301 is a highly unstable grade and AISI 316 is stable with AISI 304 in between.
The effect of microstructural stability is shown in figure 22.
As opposed to Jacobsen's results for round clinch the fatigue properties increases rapidly with increasing degree of microstructural stability for the rectangular clinch. The fact that rectangular clinches contains macrocracks (clinch size) normal to the load direction could explain the different response to the strength in the deformed (clinched) area.
Round clinched joints have about twice the fatigue strength of the rectangular clinched joints (figure 23). Fatigue strength at $2*10^6$ cycles tested with the staircase method on AISI 304 1 mm sheet is 1.23 kN for rectangular clinches and 2.6 kN for round clinches, similar to Jacobsen's results.

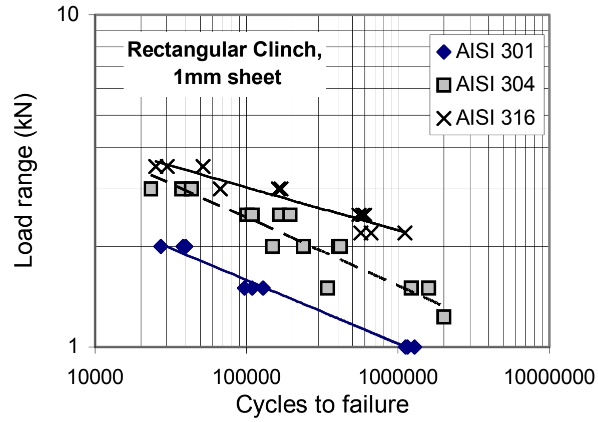


Figure 22 Fatigue properties of rectangular clinched stainless steel sheets.

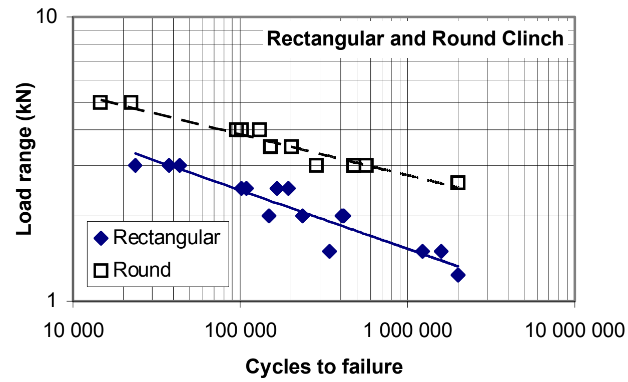


Figure 23 Fatigue properties of rectangular and round clinched stainless steel sheets.1 mm AISI 304

The fatigue strength does increase with increasing thickness (figure 24). This is most likely a result of the increased stiffness and decreased rotation, with a smaller load component in the through thickness direction.

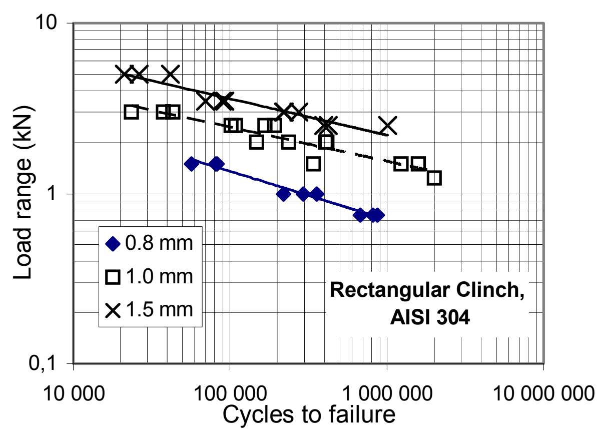


Figure 24 Fatigue properties of rectangular clinched stainless steel sheets in three different thicknesses.

ADHESIVE BONDED JOINTS

R.Boyes (15) and S.McCann (16) have studied the static and dynamic strength of adhesive bonded stainless steel lap joints.
Boyes have fatigue tested specimens of type 1 with a 40 mm overlap using 4 mm gauge AISI 304 material. In figure 25 his results using the stiff “Box” specimen are compared with results from testing of a type 3 specimen with 1.5 mm gauge sheet and with two bondline thicknesses. The adhesive used was the 3M DP 460.

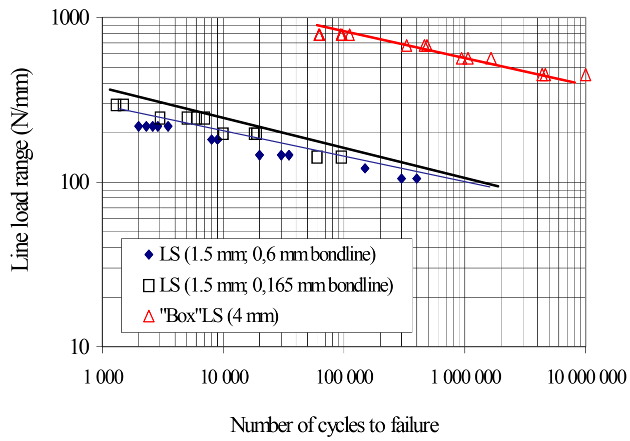


Figure 25 S-N curve for 4 mm flanged specimen type 1 and 1.5 mm specimen type 3 with bondline thickness of 0.165 and 0.6 mm. Bonded with toughened epoxy system, DP 490. (Room temperature, 20 Hz, R = 0.1)

For the 4 mm thick material using type 1 specimens the fatigue strength at 10^6 cycles is estimated to be 500 N/mm compared with 80 N/mm for the thinner material. For longer lives the increased bondline thickness does not seem to affect the strength.
McCann (16) studied the effect of surface cleaning before bonding, load ratio, test frequency and the effects of exposure to an aqueous environment on adhesively bonded 1.5 mm gauge AISI 304 stainless steel. He used type 3 specimens with 25 mm width, 12.5 mm overlap and 112 mm grip distance. DP490 toughened epoxy adhesive in 0.25 mm bondline thickness was used. All tests except those on environment are done in laboratory air at room temperature. His results are summarized in figure 26 – 29.
The effect of surface pre-treatment was substantial, with a 60 % increase from grit blasting the adherand.
The increase of R-value from 0.1 to 0.5 did not change the fatigue properties with more than 15 per cent (figure 27).
The effect of loading frequency is visible only for the lowest frequency (1 Hz) at fatigue lives longer than 500 000 cycles. This indicates that it is time elapsed rather than dynamic effects that are important.
To evaluate the effect of water on adhesive joints specimens were aged in distilled water for 4, 24, 48 and 72 weeks and then fatigue tested at 5 Hz in distilled water. All at ambient temperature. As seen in figure 29 there is a dramatic deterioration of the fatigue strength. After immersion for 72 weeks the specimen retained no fatigue strength.

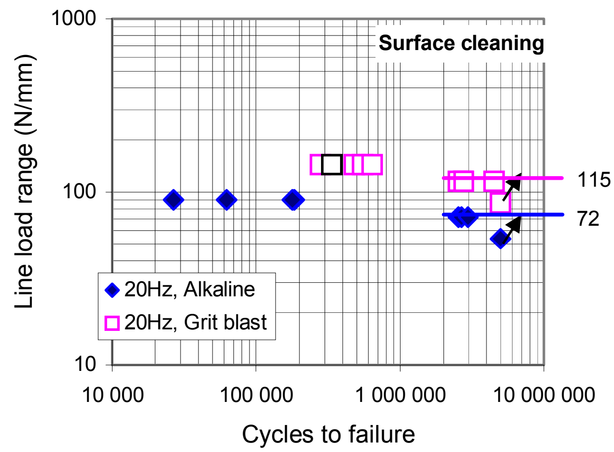


Figure 26 Fatigue of 1.5 mm AISI 304L stainless steel adhesive joints. Effect of surface cleaning.

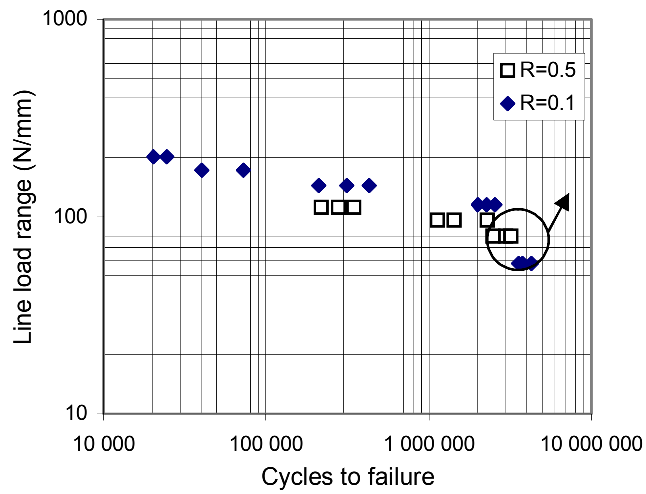


Figure 27 Fatigue of 1.5 mm AISI 304L stainless steel adhesive joints. Effect of load ratio.

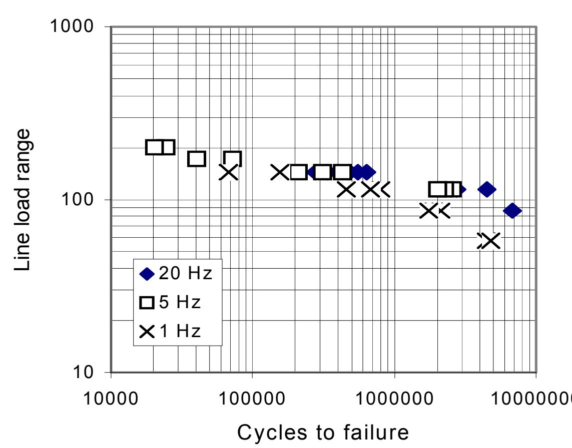


Figure 28 Fatigue of 1.5 mm AISI 304L stainless steel adhesive joints. Effect of loading frequency.

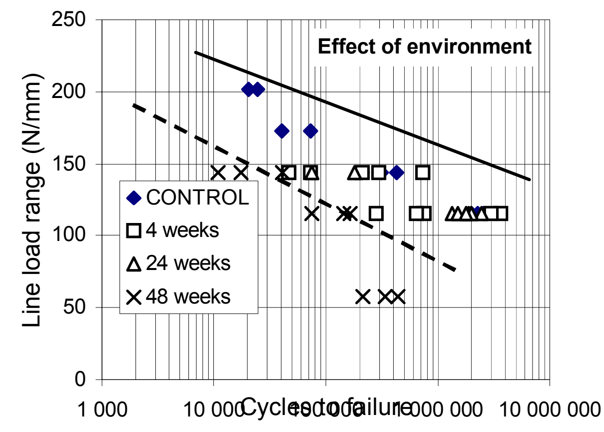


Figure 29 Fatigue of 1.5 mm AISI 304L stainless steel adhesive joints. Specimen immersed in water for 4 to 48 weeks.

Although these results from dry air testing indicate a dramatic increase in fatigue strength going from spot welding to adhesive bonding, a number of questions about adhesive bonding have to be resolved. The long term behaviour and the effect of different environments on bonded joints need a lot of attention in the future.

WELDBONDED JOINTS

The combination of spot welding and adhesive bonding (weldbonding) has been studied by M.Ring Groth (17, 18).

The welding process is important for the weldbonded joint properties, but not as significant as the adhesive process. The welding process can be varied in several ways, and still produce the desired result. The welding process may have to be adjusted to overcome the influence of the adhesive process. If the adhesive is applied first, the weld process must be compensated for this, which can be done by varying the weld force and/or the time before applying the current. This will push away the adhesive from the location of the spot weld and achieve contact between the metallic surfaces. The adhesive process will influence the welding window. The characteristics of the adhesive will play an important role, especially the viscosity of the adhesive. The denser the adhesive is the more force and/or time will be necessary to push the adhesive from the metal surfaces to put the metal surfaces in contact with each other.

Fatigue tests were performed on 4 mm thick sheets of AISI 304 using a type 1 specimen. The weldbonded fatigue test specimens were grit blasted, rinsed in water and degreased with methanol prior to bonding. The adhesive used was Ciba-Geigy, Araldite 2015.

To obtain the fatigue strength at 10^7 cycles the staircase method was used.

The results are shown in figure 30 together with the results from an identical specimen type for both spot welding and adhesive bonding. The fatigue limit for weldbonded joints is estimated to be approximately 8 kN (136 N/mm), twice that for spot welded joints but less than half of that for adhesively bonded joints. It should, however, be noted that different adhesives were used. A weldbonded joint using 3M DP 490 could give better fatigue properties based on its higher tensile strength.

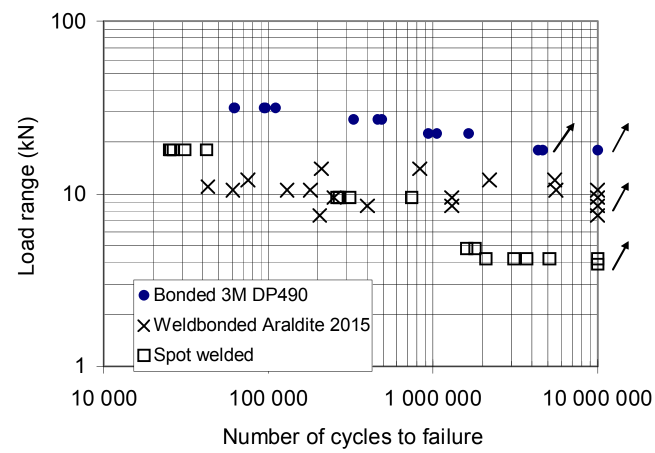


Figure 30 S-N curve for 4 mm flanged simple lap joint weldbonded with toughened epoxy system Araldite 2015. (Room temperature, 50 Hz, R = 0.05). Comparative data from Ref. (3) and (15).

LASER WELDED JOINTS

A.Kaitanov (19) and C.Dinsley (20) have tested laser welded stainless steel joints. Compared to spot welding, laser welding can be done continuously, drastically reducing the stress concentrations in the joint. Furthermore laser welding does not have the restrictions in weld area (number of nuggets per unit area) typical for spot welding, imposed by leakage current. Thus the load transfer area is less limited using laser welding.

Kaitanov investigated AISI 304 in 3.0 mm thickness and with tensile properties: $R_{p0.2}$= 320 MPa, R_m= 670 MPa.

Kaitanov showed that laser welding of lap joints can be done without affecting the aesthetic appearance on the "back" side and identified the laser welding parameters window for this feature. This is called "controlled penetration". This aesthetic constraint is sometimes imposed on structures in the transport sector.

The fatigue properties were determined for two joint types, single and double weld. The single weld was done in two variations; narrow weld (3.2 kW at 1.7 m/min) and wide weld (2.5 kW at 0.8 m/min). All welds were of the "controlled penetration" type.

The fatigue results are given in figure 31. The fatigue strength for the single narrow (0.8 mm) weld at $2*10^6$ cycles was established with a staircase test (25 specimens) to be 118 N/mm line load range with a standard deviation of 11 N/mm. Single wide welds (≈ 1.1 mm) show a distinctly higher fatigue strength but the number of tests was too small to give a value with acceptable reliability.

Dinsley (20) has studied laser lap joints between stainless steel and galvanised carbon steel. The materials are given in Table IX.

A summary of his results is given in Table X and figure 32. Because of the different thermal properties of the mild steel and the stainless steels, with a 4 to 5 times higher thermal conductivity for the carbon steel, similar heat inputs result in wider welds if the joint is welded from the carbon steel side (top material), rather than from the stainless steel side. As in Kaitanov´s study a wider weld increases the fatigue strength. The fatigue strength for the different material combinations is not significantly different from each other, with the possible exception for the 2205/GS joint with a 0.9 mm wide weld.

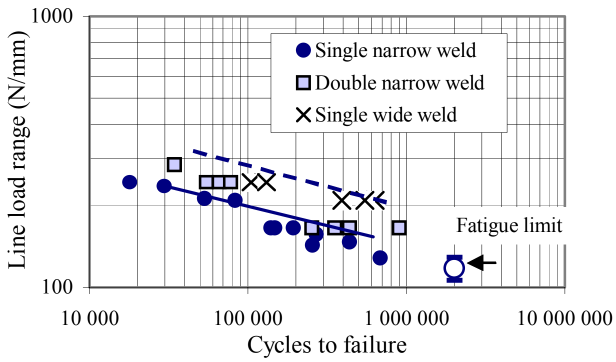


Figure 31 S-N curves for 3 mm AISI 304 laser welded simple lap shear joints. Controlled penetration.

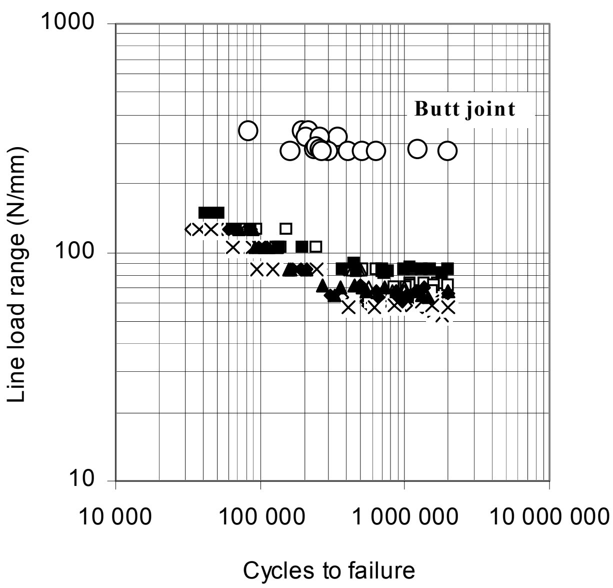


Figure 32 Fatigue properties of laser welded lap joints.

Comparing Kaitanov´s and Dinsley´s results, the fatigue strength in terms of line load range is almost linearly related to the sheet thickness at similar weld width. This means that the nominal net section stress range is equal at about 60 MPa. This is to be compared with the duplex 2101 butt weld with a fatigue strength of 278 MPa.
Linder and co-workers (21) have tested laser welded cold-worked AISI 304 with a yield strength of 552 MPa in 1.0 and 2.5 mm thickness. The tests (R=0.05) were almost entirely to < 10^6 cycles and the fatigue strength at $2*10^6$ could not be evaluated. However, for lower lives they showed that an increase of weld width for 1.0 mm sheet joints from 0.6 to 1.3 mm increased fatigue strength about 30 %. At the same weld width the strength increased 75 % by increasing sheet thickness to 2.5 mm.
Ericsson (22) studied AISI 304CS in 1 and 2 mm thickness. The fatigue strength at $2*10^6$ cycles was 60 N/mm with a standard deviation of 3.5 N/mm for 1 mm thick sheets with a 0.6 mm weld width. For 2 mm sheet with 1.0 mm weld width the fatigue strength was 75 N/mm, an increase of 25 %.

FATIGUE PROPERTIES OF JOINTS:

A COMPARISON

The results reported above are all on stainless steel, in most cases of Type AISI 304 but tested in different thicknesses and with different types of specimens. One way of comparing results is to give load ranges in “line load”, i.e. the load divided by the specimen width or pitch. This makes it possible to compare continuous joining methods like bonding and laser welding with discontinuous methods such as spot welding and clinching.
For spot welding an optimum pitch calculated from equation (1) is used in this section. Information about optimum clinch distances is not available.

Effect of material strength.

It has been shown numerous times that fatigue properties for joints in carbon steel sheets with different parent material strengths are similar. This is illustrated in figure 16 to be the case even for stainless steels. In this figure the fatigue results for different stainless steels with yield strengths in the range 290 - 725 MPa are compared.
Furthermore, results by Marples in figure 19 show that the fatigue strength for a stainless steel spot welded joint is similar to that for a galvanised carbon steel.
For round clinched joints there are indications that increased strength leads to increased fatigue strength but within a limited range since use of the clinching process set limitations on the clinchability of thicker material.

Effect of sheet thickness.

For spot welded joints the increased stiffness for thicker sheets giving higher fatigue loads per nugget seems to be neutralised by the need for increased pitch for thicker materials to avoid shunting. This is illustrated in figure 4 and Table III. The increase in pitch is to keep leak current under control.
In the sheet gauge range suitable for clinching thicker sheets show higher fatigue strength, figure 24, at least for rectangular clinches. The suitable range for round clinches is believed to be even narrower.
Limited testing has been carried out on laser welded joints with different sheet thicknesses. The results are partly obscured by a large variation in the weld widths.

However, fatigue strength in line load increases with increasing thickness. The increase is in the order of 30 N/mm per mm thickness increase up to 3 mm.
As illustrated by Boyes (15) and McCann (16) in figure 25, for adhesively bonded joints an increased thickness with an accompanying larger overlap strongly increases the fatigue strength. An increase from 1.5 mm to 4 mm thick sheets in the joint increases the fatigue strength five-fold.

Effect of testing environment.

Testing in aggressive 3% sodium chloride environment reduces the fatigue strength of spot welded AISI 304 stainless steel joints at long lives by up to 40%. Exposure of up to 2000 hours before testing did not affect the fatigue strength further. Although not tested the same response is expected for clinched joints and laser welded joints.
Stainless to galvanised steel joints have not been tested in aggressive environments, but are expected to be very sensitive due to galvanic corrosion.
The adhesive joints studied to date are very sensitive to long term exposure to water. After a 72 week exposure a toughened epoxy adhesive joints retained no fatigue strength.

Joining methods.

Spot welded and projection welded joints show similar fatigue strengths.
In the thickness range 0.8 – 1.5 mm spot welding, laser welding and adhesive bonding have similar fatigues strength, 70 N/mm.
In a dry environment adhesive bonding and combination of spot welding and adhesives have potential to give very high fatigue strengths compared with spot welding. The effect of adhesives is greater for thicker materials.
At around 1 mm thickness spot welding and rectangular clinches give similar fatigue strengths, typically 1.2 kN per nugget or clinch. Round clinches give approximately twice this fatigue strength.

ACKNOWLEDGMENTS

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NOMENCLATURE

d = nugget diameter
e = pitch or distance between nuggets
K_{eff} = effective stress intensity factor
K_{eff}^{max} = maximum effective stress intensity factor
P = load per nugget or total load
Q = line load = load per unit length of joint
$R_{p0.2}$ = Yield strength
R_m = Tensile strength
t = sheet thickness
x = distance in thickness direction from inner surface

TABLES

Table I	Nominal chemical compositions (wt.%) of materials studied.

Material	C	CR	Ni	Mo	Mn	Other
AISI 301	0.1	17	7			
AISI 304 (L)	0.02	18	10			
AISI 316	0.02	18	12	2.5		
S32101 (“2101”)	0.02	21	1.5		5	N
SAF 2304	0.02	23	4			N
S32205 (“2205”)	0.02	22	5	3		N
SAF 2507	0.02	25	7	4		N
V1437, (GS)	0.08				0.3	Al

Table II	Mechanical properties of materials tested by Linder (3) and Marples (11).

Material	Thickness (mm)	$R_{p0.2}$ (Mpa)	R_m (Mpa)	Ref.
AISI 304CS	1.5	545	750	3
AISI 304CS	3	496	782	3
AISI 304CS	4	550	760	3
AISI 304	1.0	295	598	11

Table III	Mean fatigue strength at 10^7 cycles. Fatigue strengths given as load range are determined using the staircase method. The 95% confidence limits on the estimated mean fatigue strengths are also given. Ref.(3, 4, 11)

Material AISI	Comments. Pitch / R-value	Specimen Type / Width (mm)	Thickness (mm)	Fatigue strength Line load range (N/mm)	95% conf. limits (N/mm)	Fatigue strength Stress range (MPa)	Fatigue strength Load range (kN)
304CS	24 mm / 0.05	1 / 35	1.5	86.3	± 9.6	57.5	2.07
304CS	30 mm / 0.05	1 / 48	1.5 / 3	67	± 10	44.7	2.01
304CS	45 mm / 0.05	1 / 48	3	66.9	± 5.6	22.3	3.01
304CS	59 mm / 0.05	1 / 56	4	70.5	± 5.9	17.6	4.16
304CS	59 mm / 0.05	1 / 56	4	63.6	± 4.9	15.9	3.75
304CS	59 mm / 0.67	1 / 56	4	49	± 4.6	12.2	2.89
304CS	24 mm / 0.05	2 / 50	1.5	8.75	± 2.08	5.8	0.21
304CS	59 mm / 0.05	2 / 50	4	32.7	± 2.4	8.2	1.93
304CS	24 mm / 0.05	3 / 46	1.5	75.8	± 5.8	50.6	1.82
304CS	59 mm / 0.05	3 / 60	4	63.6	± 4.9	15.9	3.75
304CS & 304	83 mm / 0.05	H / 150	4	70			3
304	17 mm / 0.1	3 / 45	1.0	70.7	± 5.0	70.7	1.20

Table IV Normalised stress intensity factor for the different specimen types studied. Ref.(1).

Specimen type	Sheet thickness (mm)	Nugget size (mm)	K_{eff}^{max} / P (MPa√m / kN)
1	1.5	6	2.8
1	3.0	8	1.5
1	4.0	9	1.2
1	1.5 / 3.0	6	2.2
2	1.5	6	14.7
2	4.0	9	3.2
3	1.5	6	2.9
3	4.0	9	1.3

Table V Mechanical properties of the duplex stainless steels studied.

Material type	Ref.	Thickness (mm)	$R_{p0.2}$ (MPa)	R_m (MPa)
2304	Linder(4)	4	545	720
2101	Wray(9)	1.0	650	800
2304	"	1.0	675	804
2205	"	1.0	658	803
2507	"	1.0	725	939

Table VI Fatigue strength of spot welded duplex stainless steel. Ref (3, 4, 9).

Duplex Material	Comments Pitch / R-value	Specimen Type / Width (mm)	Thickness (mm)	Fatigue Strength Line load range (N/mm)	95% conf. Limits (N/mm)	Fatigue Strength Stress range (MPa)	Fatigue Strength Load range (kN)
2101	25 mm / 0.05	3 / 46	1.0	69	± 9.3	68.7	1.17
2304	25 mm / 0.05	3 / 46	1.0	70	± 7.7	70.3	1.19
2304	59 mm / 0.05	1	4.0	87	± 5.9	21.7	5.11
2304	59 mm / 0.05	1	4.0	87	± 19.7	21.8	5.15
2304	59 mm / 0.05	2	4.0	36	± 2.8	8.9	2.11
2205	25 mm / 0.05	3 / 46	1.0	61	± 9.2	61	1.04
2507	25 mm / 0.05	3 / 46	1.0	66	± 6.6	66	1.12
With Expulsions							
2304	24 mm / 0.05	3 / 46	1.0	74	±19	74	1.26
2205	24 mm / 0.05	3 / 46	1.0	81	±24	81	1.37

Table VII Estimates of fatigue strength at 10^7 cycles in aqueous 3%NaCl. Ref.(10).

Material	Fatigue strength Load range (kN)	95 % conf. limit	Number of specimen used
AISI 304, air	4.16	± 0.29	10
AISI 304, 3%NaCl	2.62	± 0.36	10
SAF 2304, air	5.15	± 1.16	9
SAF 2304, 3% NaCl	2.85	± 0.36	9
SAF 2304, 3% NaCl pre-exposed 1200 – 2000 hours	2.73	± 0.35	9

Table VIII Properties of spot welded sheet steels. Stainless steel spot welded to galvanised carbon steel. Ref.(11).

Material	Thickness (mm)	$R_{p0.2}$ (MPa)	R_m (MPa)	Comments
AISI 304	1.0	295	598	2B, Annealed
V1437	1.2	260	380	7 μm Zn coat

Table IX Strengths of materials tested by Dinsley (20).

Material	Thickness (mm)	R_p (MPa)	R_m (MPa)
V1437	1.2	300	420
AISI 304	1.0	310	630
2205	1.0	680	850
2205	0.78	580	702
2101	1.0	650	800

Table X Fatigue strengths of Galvanised steel / Stainless steel laser welded lap joints. Ref. (20)

Joint Materials Top	Bottom	Fatigue strength (N/mm)	Standard deviation (N/mm)	Weld width (mm)
1 mm 304	1.2 mm Galv.	60.3	3.4	1.3
1.2 mm Galv.	1 mm 304	71.1	4.6	1.4
0.78 mm 2205	1.2 mm Galv.	58.1	≈ 6	0.9
1.2 mm Galv.	0.78 mm 2205	66.9	3.1	1.2
1.2 mm Galv.	1 mm 2205	66.1	4.3	
1.2 mm Galv.	1 mm 2101	67.5	3.7	
1 mm 2101	1 mm 2101	83.9	3.9	1.4
1 mm 2101 Butt joint		278	7	
The four first joint types were produced using a 5kW CO_2 laser welder (3.8 kW at work piece) with a 2.3 m/min welding speed. The last four were welded with a 2 kW CO_2 laser welder at 1 m/min.				