OVERLAP JOINING OF STAINLESS STEEL SHEETS.

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

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INTRODUCTION

Stainless steel in structural applications is one of 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 segment. A good example of a growing sub-segment is the transport sector, e.g. busses and trains.

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, establish structural elements behaviour under static and dynamic loads, develop design guides etc.

This presentation is a short overview over the projects AvestaPolarit Research Foundation have been and are pursuing in the area of joining of stainless steel sheets.

SINGLE OVERLAP JOINT

Some basic types of lap joints are schematically shown in figure 1. In this figure the joining technique is assumed to be adhesive bonding but could as well be spot welding, laser welding, clinching, riveting or some combination of these. The simple lap joint with some modification as in figure 1f is for obvious reason the most widely used.

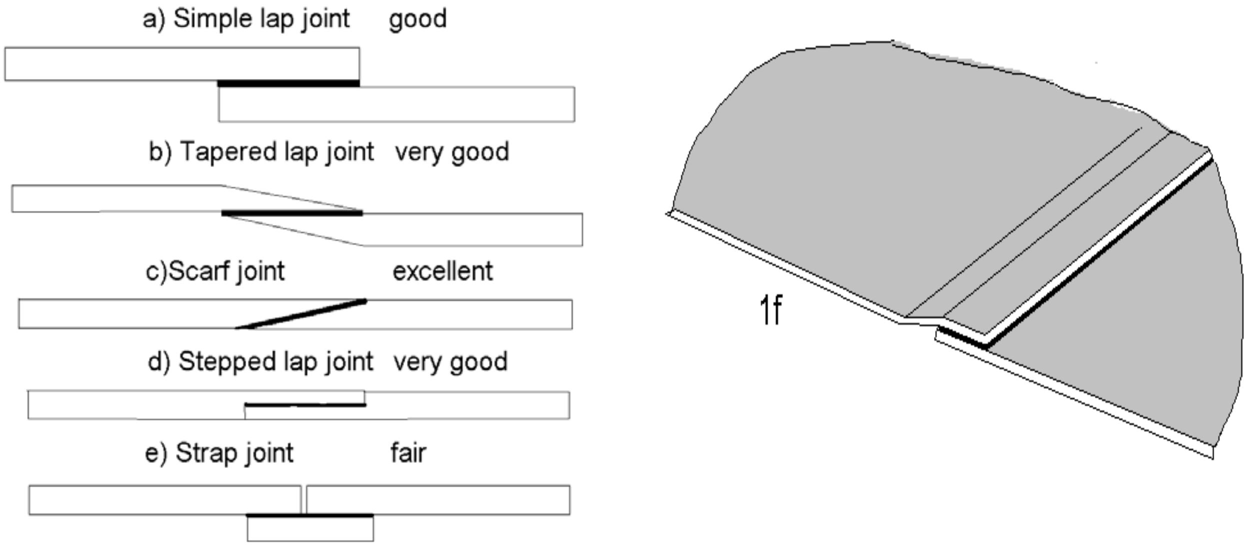

Figure 1 Lap joints for sheet materials.

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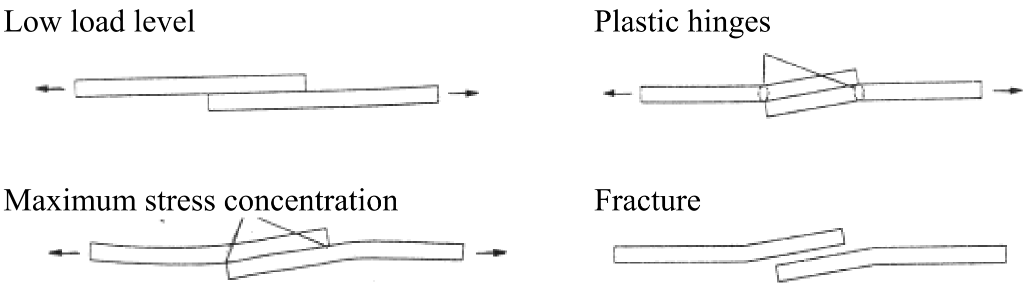


Low load level

Plastic hinges

Maximum stress concentration

Fracture

Figure 2 Deformation of lap joint during loading.

The eccentricity of the load path, figure 2, result 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 have been illustrated a number of times and over the last decades mostly with FEM techniques, figure 3 (1).

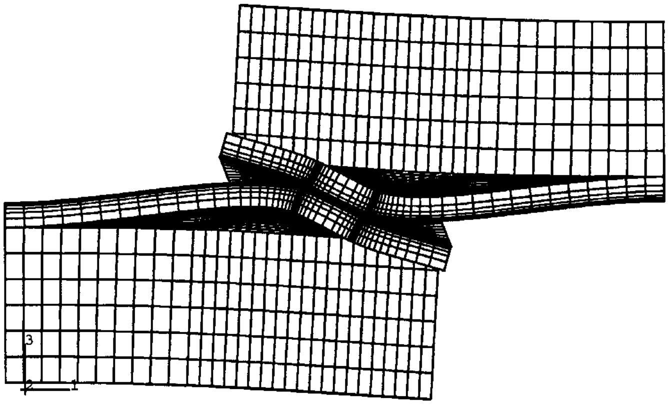


Figure 3 FEM analysis of spot welded joint showing rotation of joint (1).

To evaluate the effect of different joint parameters on joint rotation and the resulting development of opening mode tensile load (or peel stresses) a simple analytical model using beam bending theory have been developed.
In the simplest form the joint can be approximated as shown in figure 4.

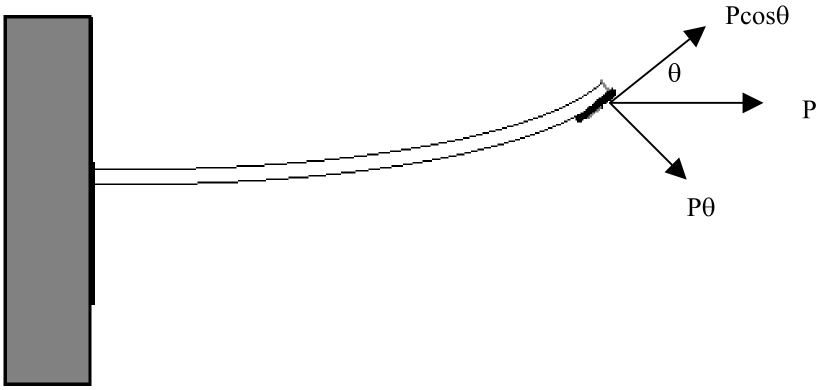


Figure 4 Schematic load distribution in a lap joint.

The force transferred over the joint can be divided into a pure shear load resulting in a moment $M = P * \frac{(h+t)}{2}$ and a transverse load $P_{Peel} = P * \theta$

Using beam theory the rotation due to the moment and the peel force can be calculated as

$$\theta_M = 6 * \frac{P * (h+t) * a}{E * b' h^3} \quad \text{and} \quad \theta_{Peel} = \frac{6 * P * a^2}{E * b * h^3} * \theta_{Total}$$

Since $\theta_{Total} = \theta_M - \theta_{Peell} = \theta$ the total (net) rotation is

$$\theta = \frac{6 * P * (h+t) * a}{E * b * h^3} - \frac{6 * P * \theta * a^2}{E * b * h^3} \theta \quad \text{or} \quad \theta = \frac{h+t}{a * \left[1 + \frac{E * b * h^3}{6 * P * a^2} \right]}$$

The rotation of the joint and, since $P_{Peel} = P * \theta$, the transverse force increases with increasing load (shear stress) . The effect of sheet thickness and length (slenderness) is more complex as shown in figure 5, but for sheet thickness up to 4 mm the rotation increases with increasing sheet thickness and decreasing slenderness. Since lap joint strength is highly influenced by the transverse peel forces this observation can explain why bonded thin high strength sheet joints can have a higher strength than thicker sheet joints. To reduce the rotation for a given sheet thickness and load the stiffness can be increased with corrugation or with flanges as will be further illustrated.

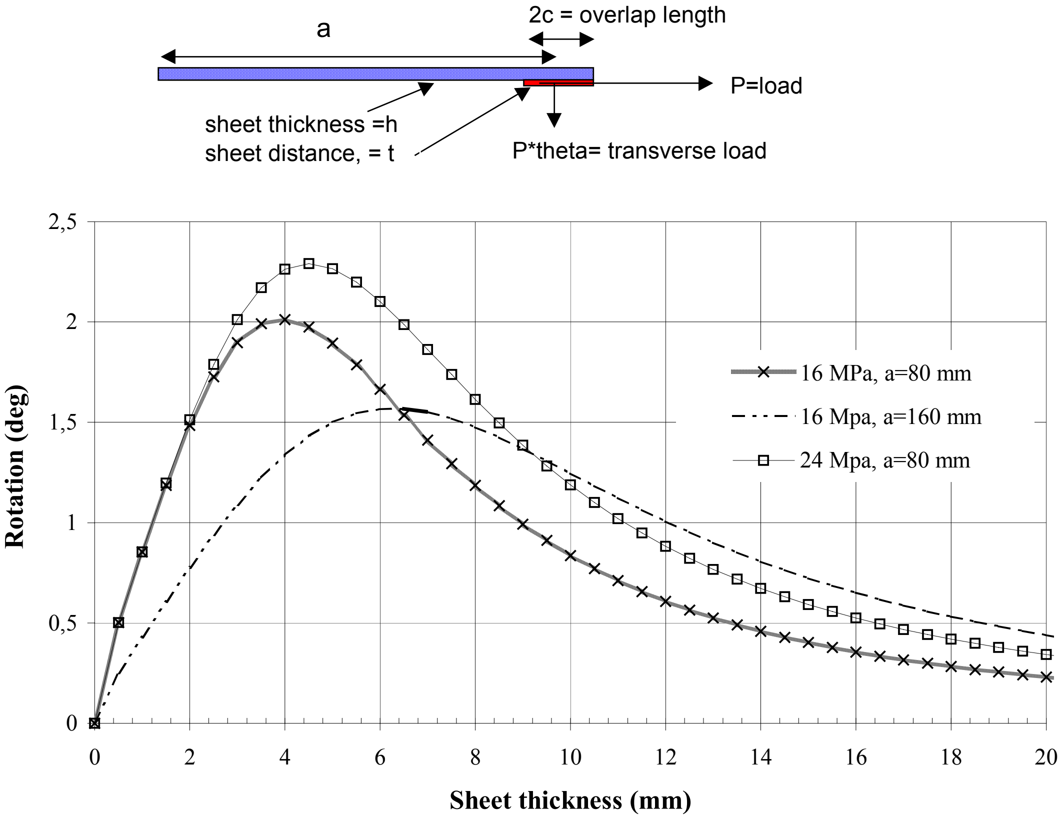


Figure 5 Elastic rotation of lap joint with different sheet thickness. Load level given as shear stress on the overlap length 2c=40 mm.

SPOT WELDED JOINT

Linder and co-workers (1-3) at The Swedish Institute for Metals Research have studied the spot welded joint particular with reference to fatigue behaviour.

Three different joint configurations (test specimen types) have been studied, figure 6.

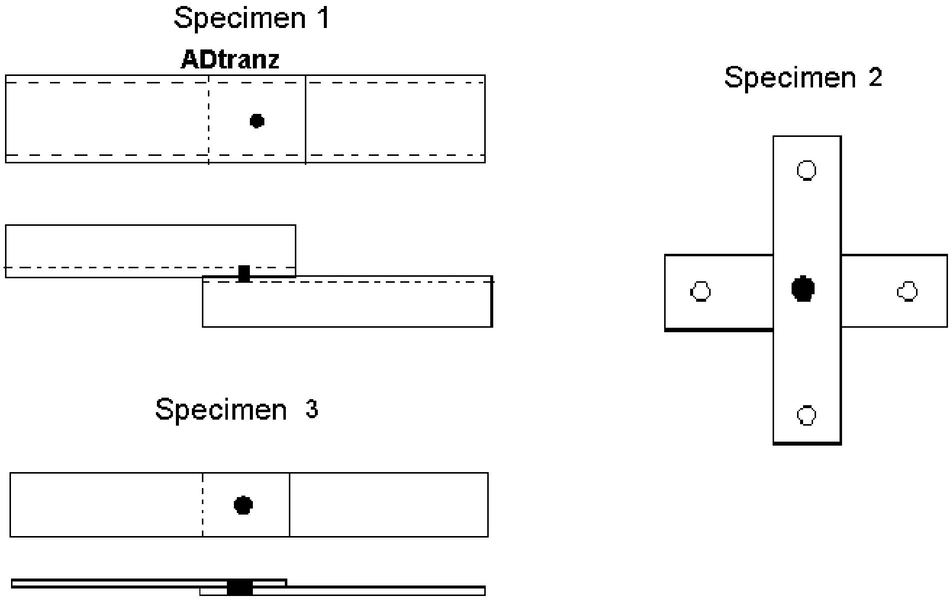


Figure 6 Lap joint specimens used to study spot welding, adhesive bonding and weldbonding.

Specimen type 3 is the standard single over lap joint. To increase the stiffness and reduce transverse forces specimen type 1 was designed with stiffening flanges. This specimen type is sometimes called ADTranz 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.

Stress intensity factor calculation

The stress intensity factors 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 results from this calculation is presented in the form of an effective stress intensity factor, K_{eff}, defined as:

$$K_{eff} = (K_I^2 + K_{II}^2 + K_{III}^2/(1-\nu))^{1/2}$$

For specimen type 1 and 3 the maximum effective stress intensity factor, K_{eff}^{max} , was exclusively found along the loading axis where fatigue cracks also were observed to initiate. For peel loaded specimen (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 7 for type 1. The shear to peel ratio is 1/0.17 for the flanged specimen type 1, and 1/0.37 for the single overlap specimen type 3 for a thickness of 4 mm.

K_{eff}^{max} for the three specimen types with different sheet thickness are given i Table I.

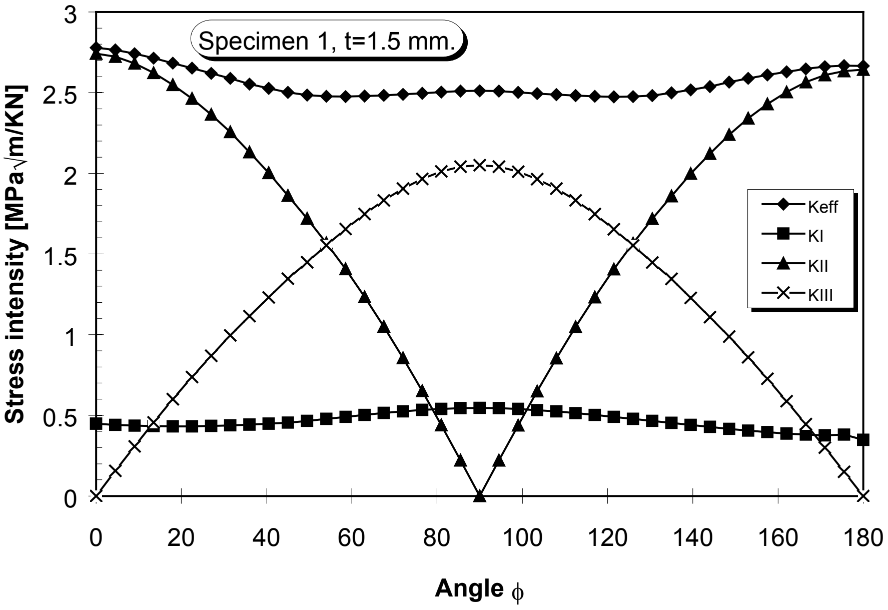


Figure 7. Variation of stress intensity factor for Type 1 specimen.

Table I Normalised stress intensity factor for the different specimen types.

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

Materials

The materials tested were the austenitic grade EN 1.4301 (AISI 304) in prestrained condition and the duplex grade EN 1.4362 ("2304"). Mechanical properties are given in Table II

Table II Mechanical properties of materials tested.

Material US Standard	European Standard	AvestaPolarit grade	$R_{p0.2}$ (Mpa)	R_m (Mpa)
AISI 304	1.4301	18-9	535	690
AISI 304 (B)	1.4301	18-9	550	760
S32304	1.4362	SAF 2304	545	725

Fatigue properties.

Fatigue testing were performed with the specimen types shown with sheet thickness 1.5, 3 and 4 mm . The material was in most cases EN 1.4301 (AISI 304) but duplex EN 1.4362 (“2304”) were also tested using 4 mm thick material. The results are given in Table III and figure 8, and as Wöhler type curves in figure 9.

The fatigue limit for 1.4301 (304) expressed in load range varied between 0.21 kN for specimen type 2, thickness 1.5 mm. to 4.16 kN for type 1, thickness 4 mm.

All load ranges for the failed specimens were recalculated using K_{eff}^{max} in Table I. The stress intensity ranges, $\Delta K = \Delta P * K_{eff}^{max}$, versus number of cycles to failure for all specimen types, sheet thickness and steel grades are shown in figure 10.

In figure 11 the two materials tested are separated. The results given in Table II, and figures 9 and 11 show that lap joints of the duplex grade have slightly higher fatigue strength than austenitic 1.4301 (304), both at the same tensile strength level.

Conclusions.

- Fatigue strength at 10^7 cycles for shear loaded joints are in the order of 10% of joint static strength.
- Fatigue strength of spot welded joints are higher for shear loading than for peel loading.
- Fatigue strength for the prestrained, austenitic grade 1.4301 (304) is similar, although slightly lower, to that of annealed, duplex 1.4362 (“2304”).
- The important parameter for fatigue failure, independent of specimen type (loading mode) and sheet thickness, is the stress concentration in the weld nugget described by the stress intensity factor range.

Table III Mean fatigue strength at 10^7 cycles. Fatigue strength given as load range, ΔP, are determined using the stair case method. R=0.05 if not specified.

Material AISI	EN	Comments	Specimen Type	Thickness (mm)	Fatigue Strength ΔPmean (kN)	95% conf. Limits (kN)
304	1.4301	Air	1	1.5	2.07	± 0.23
304	1.4301	Air	1	1.5 / 3	2.01	± 0.30
304	1.4301	Air	1	3	3.01	± 0.25
304	1.4301	Air	1	4	4.16	± 0.35
304 (B)	1.4301	Air	1	4	3.75	± 0.29
304	1.4301	Air(R00.67)	1	4	2.87	± 0.27
304	1.4301	Air	2	1.5	0.21	± 0.05
304	1.4301	Air	2	4	1.93	± 0.14
304	1.4301	Air	3	1.5	1.82	± 0.14
304	1.4301	Air	3	4	3.75	± 0.29
304(B)	1.4301	3%NaCl	1	4	2.61	± 0.36
"2304"	1.4362	Air	1	4	5.11	± 0.35
"2304"(B)	1.4362	Air	1	4	5.15	± 1.16
"2304"	1.4362	Air	2	4	2.11	± 0.14
"2304"	1.4362	3%NaCl	1	4	2.85	± 0.36
"2304"	1.4362	3%NaCl*	1	4	2.73	± 0.35

(B) second material batch

* pre-exposed 1200-2000 h in 3%NaCl

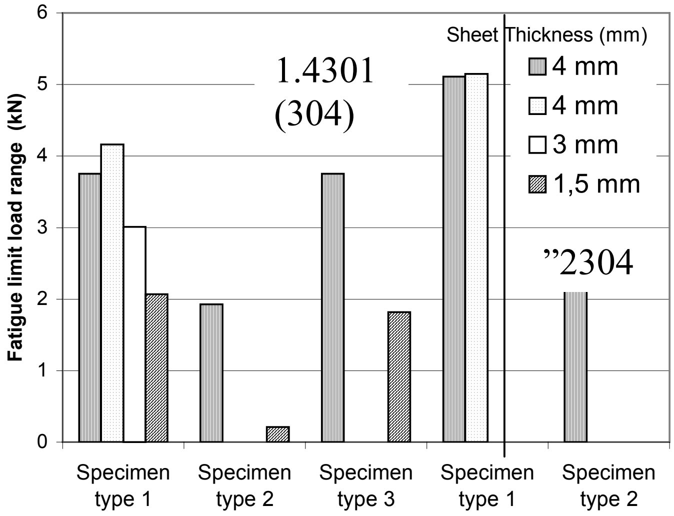
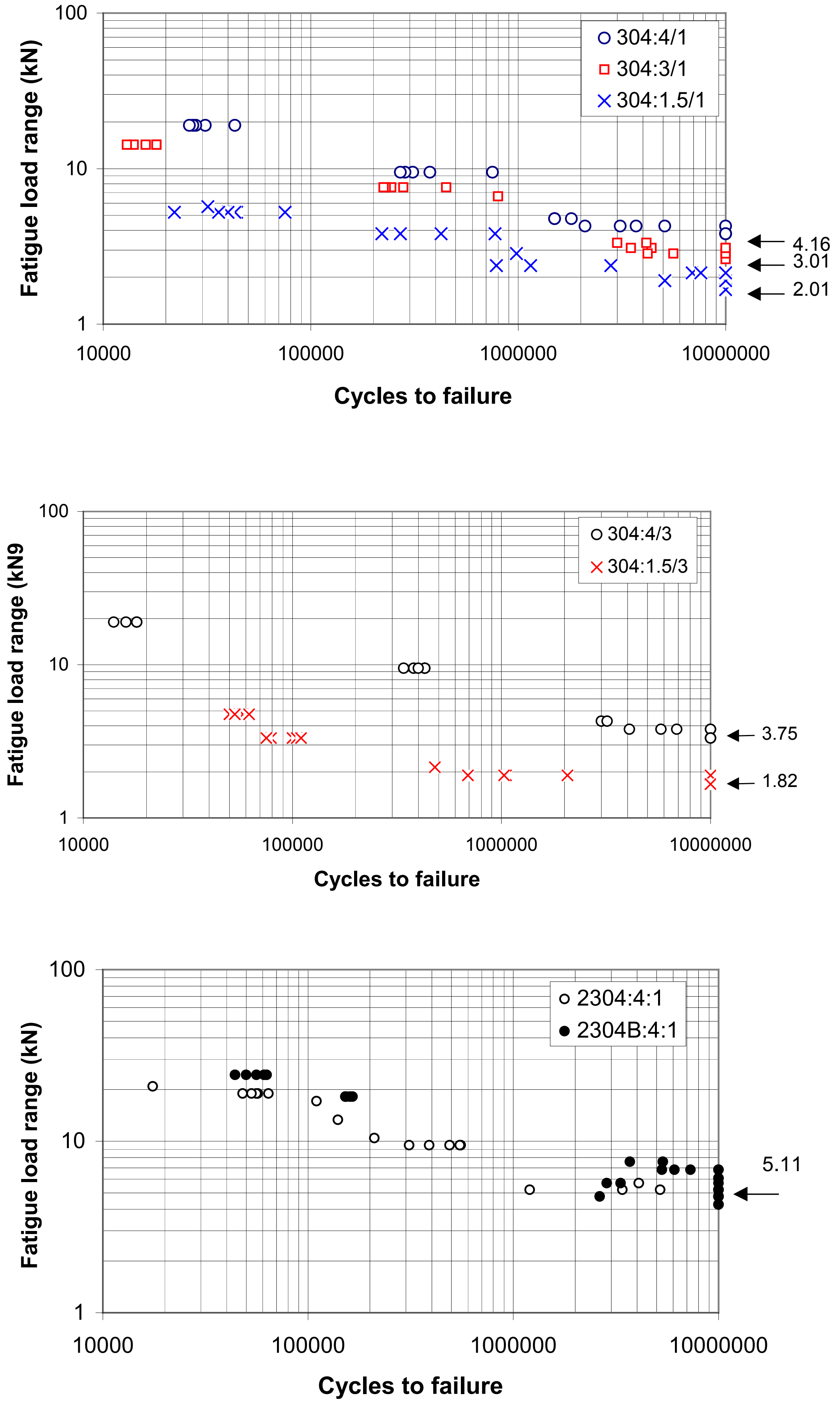


Figure 8 Fatigue strength at 10^7 cycles (from Table III)

Figure 9. Results from fatigue tests of 1.4301 (304) at 5-50 Hz and room temperature



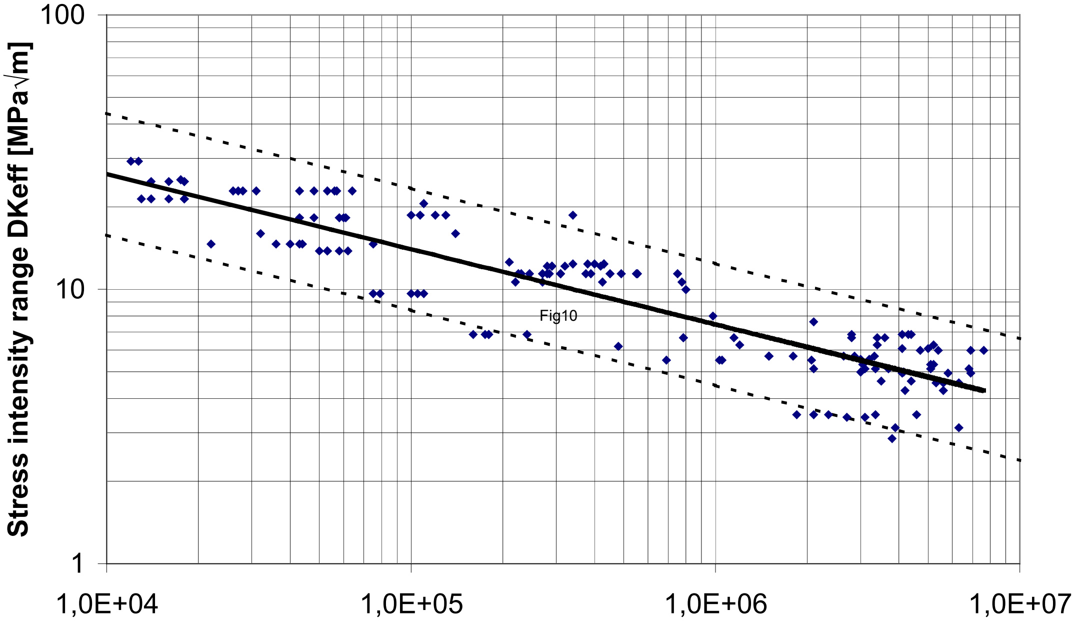


Figure 10. Stress intensity ranges versus number of cycles to failure for all specimen types, sheet thickness and steel grades. 95% confidence limits are shown.

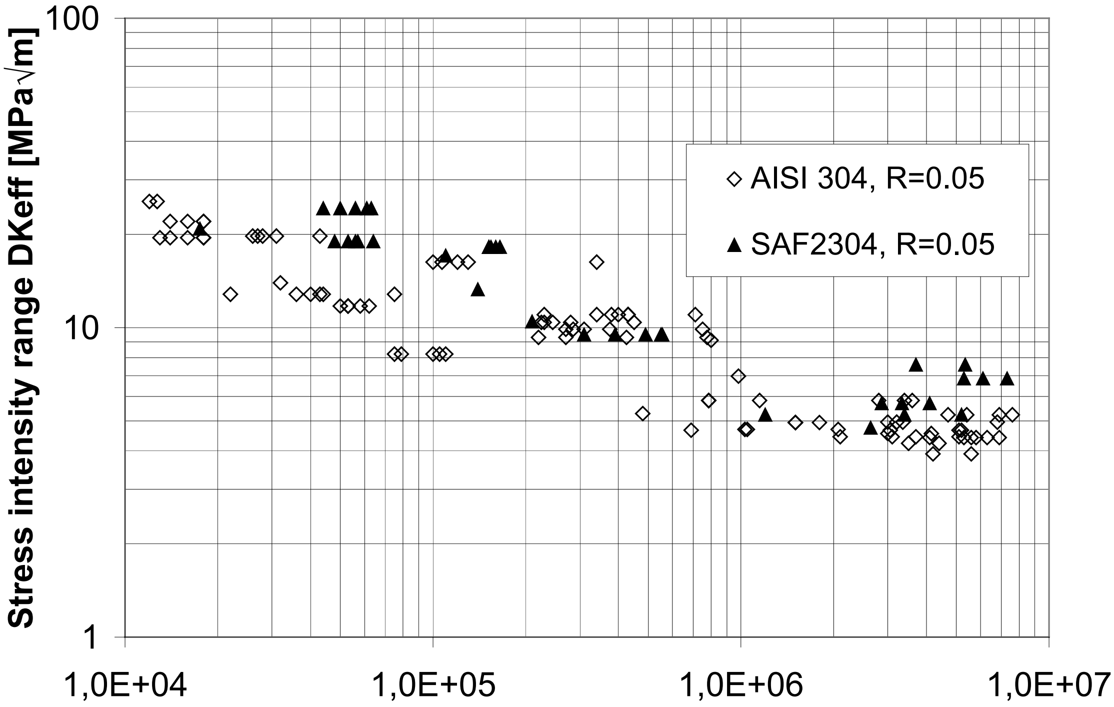


Figure 11. Stress intensity ranges versus number of cycles to failure for specimen types 1 and 2, all sheet thickness and with steel grades separated.

ADHESIVE BONDED JOINT

R.Boyes (4) at Sheffield Hallam University have studied static and dynamic strength of adhesive bonded stainless steel lap joints.

Static strength

In a screening test to find an adhesive for stainless steels with a good combination of shear and peel strength the adhesives given in Table IV were investigated.

Table IV. Tested adhesives and their curing requirements.

ADHESIVE (3M designations)	CURING REQUIREMENT
DP 460: Two-component, cold-cure epoxy	7 days at 23 °C
DP 490: Two-component, cold-cure epoxy	7 days at 23 °C
9323 B/A: Two-component, cold-cure epoxy	5 days at 23 °C
7823 S: One-component, heat-cure epoxy	40 minutes at 180 °C
3532 B/A: Two-component, cold-cure polyurethane	2 days at 23 °C
DP 801: Two-component, cold-cure modified acrylic	30 minutes at 23 °C

The adherend was a 1,5 mm thick EN 1.4306 (AISI 304L) stainless steel sheet with a 2B surface finish. For the floating roller peel test the flexible adhered was a 0,5 mm thick sheet of EN 1.4306 (AISI 304L). Three different surface treatments were studied:

- As-received, alkaline degreased, $R_a = 0.15\ \mu m$
- Mechanically roughened with grit-blasting. $R_a = 1.1 \mu m$
- Chemically etched. $R_a = 1.8\ \mu m$

For the shear strength a 25 mm wide single over-lap specimen was used with an overlap of 12.5 mm. The shear strength results are given in Fig. 12 and peel strength in Fig.13.

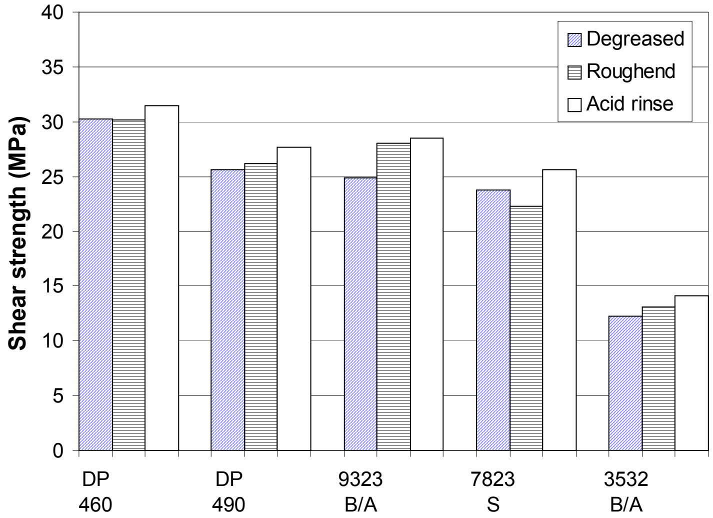


Figure 12 Initial shear strengths of adhesive-bonded EN 1.4306 (AISI 304L) stainless steel lap joints.

The best performance in terms of mean apparent shear strength came from those joints bonded with the two-part, cold-cure epoxy system DP 460. The mean strength of the joints incorporating the alkaline degreased adherends and the mechanically roughened adherends was essentially the same and the joint incorporating the acid rinsed adherends performed only slightly better.

The poorest performance came from those joints bonded with the two-part, cold-cure polyurethane system 3532 B/A. Although a slight improvement was observed after surface treatments, the improvement was small, and the result was marred by the degree of scatter displayed by the joints incorporating the alkaline degreased adherends.

The joints bonded with the two-part, cold-cure epoxy system DP 490 and the two-part, cold-cure epoxy system 9323 B/A performed well in the tests. The mean apparent shear strengths of mechanically roughened adherends were similar and the joints incorporating the acid rinsed adherends performed slightly better, although this result was marred by the extent of the scatter displayed by these joints.

The most consistent values observed were those of the joints incorporating mechanically roughened adherends, with the exception of those bonded with the one-part, hot-cure epoxy system 7823 S, where joints incorporating acid rinsed adherends faired better.

The general observation that a very good shear strength is associated with poor peel strength is confirmed by the results given in Fig.12 and 13.

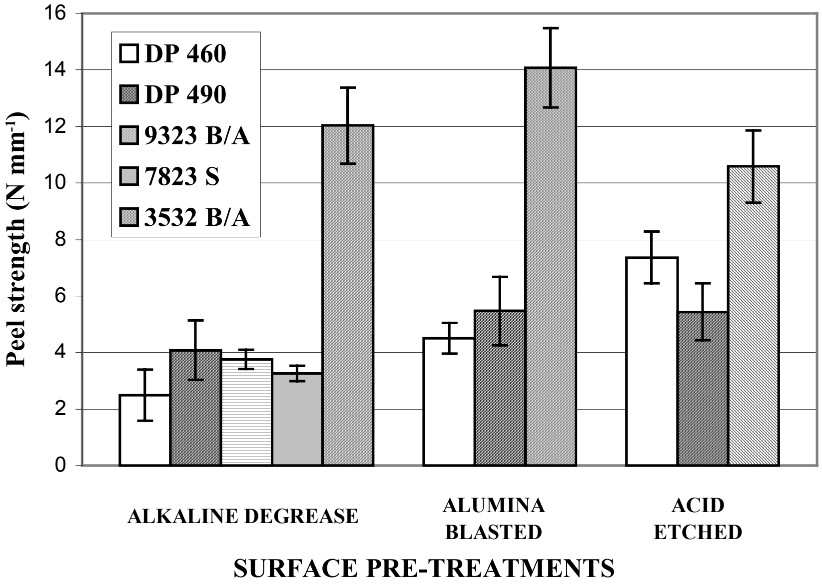


Figure 13 Floating roller peel strength of 1.4306 (304L) stainless steel/adhesive joints.

Effect of stainless steel grades on joint tensile strength.

As illustrated above the joint will rotate under tensile loads due to the eccentricity of the load line. The amount of the elastic rotation depends on the stress level, and the specimen slenderness. The transition from elastic to plastic rotation depends on the yield strength of the adherends.

The rotation of the joint creates peel stresses at the end of the overlap. Large rotations, created either by high elastic stresses or plastic deformation, leads to high peel stresses and fracture since most adhesives are sensitive to peel stresses.

An illustration of the geometrical and strength effects on the shear strength of specimen type 1 over-lap joint is shown in Fig. 14.

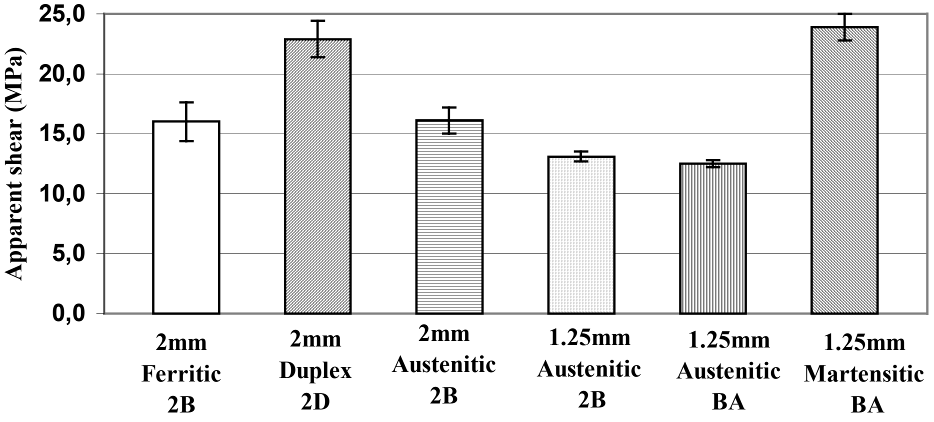


Figure 14. Apparent shear strength of adhesive-bonded stainless steel joints (2B) pickeled surface; (BA) bright annealed; (2D) semi-bright finish.

The material studied, surface finishes, yield and overlap shear strength are given in Table V.

Tabell V Sher strength for adhesive bonded lap joints.

Stainless Steel Type	Surface	Thickness (mm)	Yield strength $R_{p0.2}$ (MPa)	Shear strength (MPa)	Scatter (MPa)
Ferritic	2B	2	340	16.0	1.0
Duplex	2D	2	540	22.9	0.9
1.4306 (304L)	2B	2	310	16.1	0.7
1.4306 (304L)	2B	1.25	310	13.1	0.3
1.4306 (304L)	BA	1.25	310	12.5	0.2
Martensitic	BA	1.25	780	23.9	0.7

In figure 15 the joint tensile strength is shown as a function of the **yield strength of the adherends**. Except for the highest yield strength material (martensitic) the joint strength increases liner with adherend yield strength.

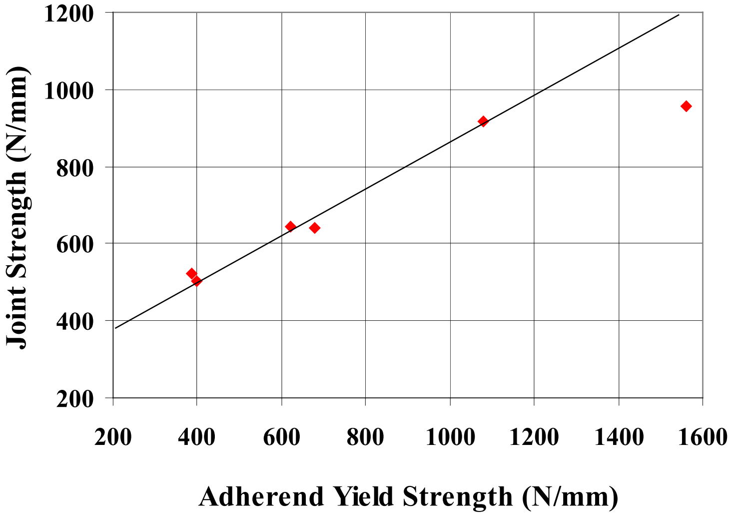


Figure 15 Joint strength versus adherend yield strength ($R_{P0.2}$*t).

The somewhat surprising result that high-strength adherends give a high strength of the adhesive layer finds its explanation in the rotation behaviour of the joint. As seen in Fig. 16 a full utilisation of the high strength of the martensitic and duplex grades is not possible at constant overlap because of the large elastic rotation associated with high stresses. An increase of the overlap should decrease the elastic rotation and thus give higher relative strength for the high-strength stainless steels.

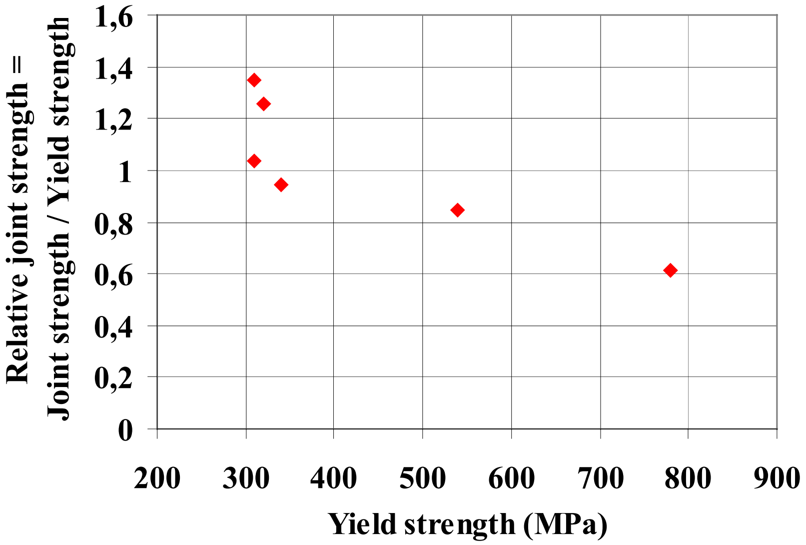


Fig. 16 Relative joint strength versus Yield strength ($R_{p0.2}$).

Fatigue properties of adhesive joints.

Specimens of type 1 using 4 mm thick 1.4301 (304) material were fatigue tested. The S-N curve in figure 17 indicate a fatigue limit of 20 kN compared with 4 kN for the spot welded specimen (figure 9, top curve).

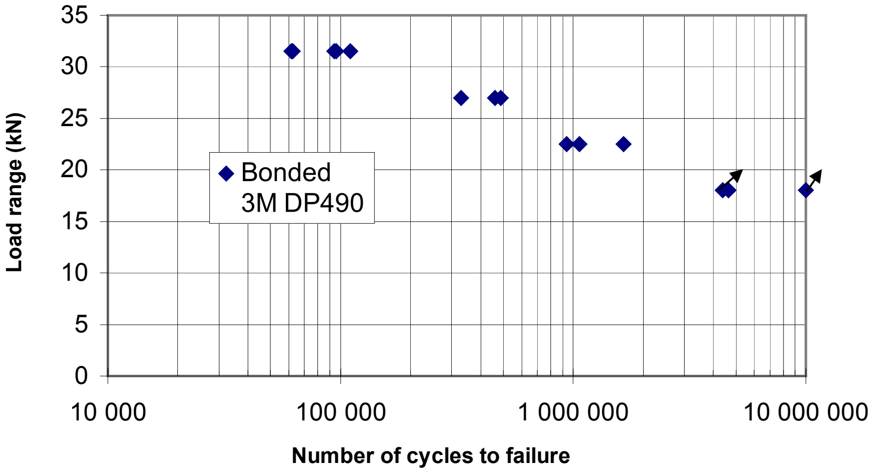


Figure 17. S-N curve for 4 mm flanged simple lap joint (Specimen type 1) bonded with toughened epoxy system, DP 490. (Room temperature, 20 Hz, R = 0.1)

Although these results 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 environment of bonded joints need a lot of attention in the future. Additional fatigue studies on adhesive bonded joints are under way at Sheffield Hallam University (4).

WELDBONDED JOINT

The combination of spot welding and adhesive bonding (weldbonding) have been studied by M.Ring Groth (6,7) at Luleå University of Technology.

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. Spot welding is mainly governed by the weld current, the weld time and the weld force. Spot welds are often characterised by their size, and a wide selections of the parameters mentioned can give the same size of the nugget. This combination of parameters are often called the welding window. The adhesive process will influence this window. Here the characteristics of the adhesive will play an important role, especially the viscosity of the adhesive. The more dense 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 properties of weldbonded joints.

Fatigue tests were performed on 4 mm thick sheets of EN 1.4301 (AISI 304) using specimen Type 1. The weldbonded fatigue tests specimens were gritblasted, rinsed in water and degreased with methanol prior to bonding. The adhesive used was Araldite 2015 from Ciba-Geigy.

The adhesives Araldite 2015 and DP 490 are both toughened 2-component epoxy systems. The two adhesives have not been tensile tested under identical conditions - the same material, surface treatment, thickness and specimen type – but type 1 specimen with as-received and degreased surface were tensile tested using 1.4301 (304) material but with different thickness. Table VI give testing conditions and test results.

Table VI Tensile testing of adhesive joints using two 2-component, toughened epoxy.

Adhesive	Specimen Type	Sheet Thickness (mm)	Adhesive Thickness (mm)	Apparent joint shear strength (Mpa)
Araldite 2015	1	4	0.4	9
DP 490	1	2	0.4	16

Because of the different thickness tested results can not be directly compared but it is obvious that DP 490 lap joins have higher strength than Araldite 2015, perhaps as much as a factor of two.

To obtain the fatigue strength at 10^7 cycles the staircase method was used. Here a run-out specimen is defined as one for which the relative (present divided by initial) stiffness has not dropped below 10%. To obtain Wöhler curves, specimens were tested at a few different load levels above and around the determined fatigue strength. The test frequency was kept constant at 50 Hz and the load ratio was R=0.05.

The results are shown in figure 18 together with the results on identical specimen type for both spot welding and adhesive bonding. The fatigue limit for weldbonded joints is estimated to be approximately 8 kN, twice that for spot welded joints but less than half of that for adhesive bonded joints. It should, however, be noted that different adhesives were used. A weldbond using DP 490 could give better fatigue properties based on its better tensile strength.

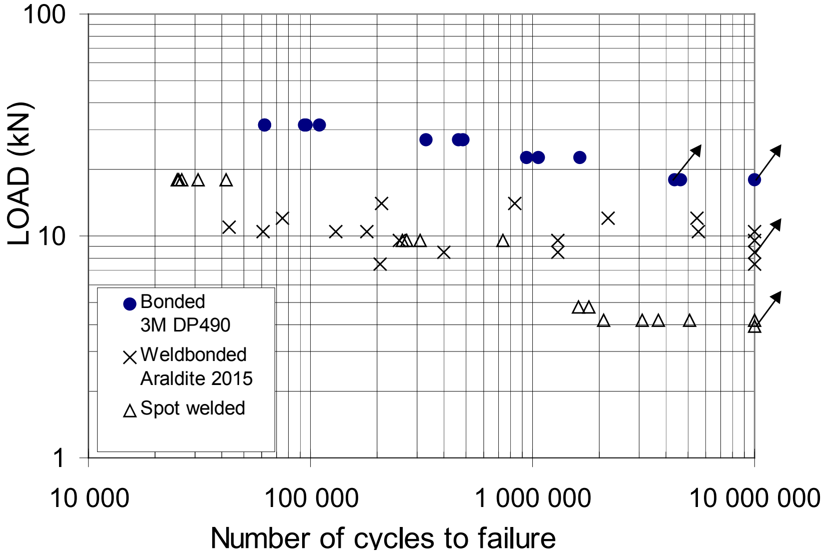


Figure 18. S-N curve for 4 mm flanged simple lap joint weldbonded with toughened epoxy system Araldite 2015. (Room temperature, 50 Hz, R = 0.05)

OTHER TYPES OF JOINING:

Laser welded joint.

A.Kaitanov (8) at State University of Marine Technology, St.Petersburg, is studying 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 leak current. The load transfer area has thus less limitation using laser welding.

The material investigated was a EN 1.4301 (AISI 304) in 3.0 mm thickness and with tensile properties: $R_{p0.2}$= 320 MPa, R_m= 670 MPa.

The relation between weld area (weld width) and tensile strength of a laser welded specimen type 3 is shown in figure 19. These results indicate a possibility to create a overlap joint with high strength and, because of the low stress concentration, very good fatigue properties.

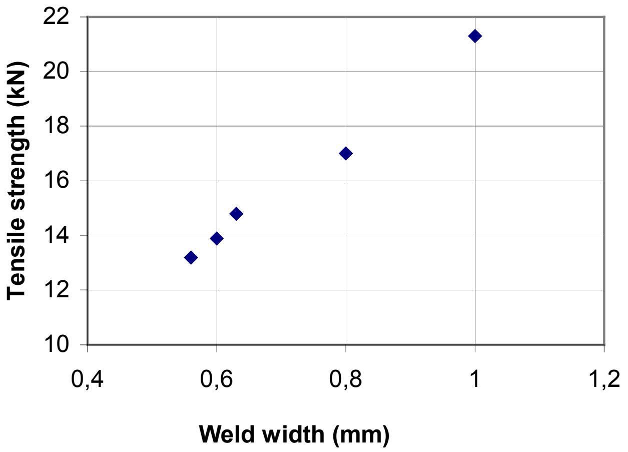
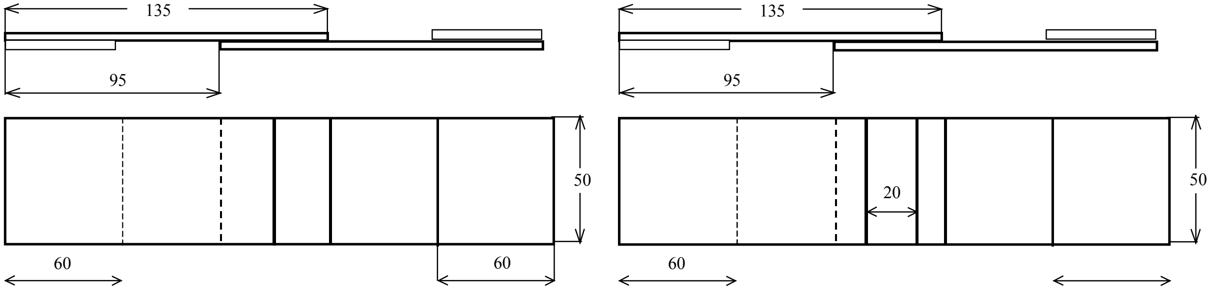


Figure 19 Tensile strength versus weld width for laser welded 3 mm stainless steel. Simple over lap specimen.

Kaitanov have shown that laser welding of lap joints can be done without affecting the aesthetic appearance on the "back" side and identified the laser welding parameter window for this feature. This aesthetic constraint are sometimes imposed on structures in the transport sector.

The fatigue properties were determined for two joint types , single and double weld, as shown in figure 20.



Single weld (Specimen Type 3) Double weld

Figure 20 Laser welded fatigue specimens.

The single weld was done in two variations; narrow weld (high power, high speed) and wide weld (lower power, low speed). All welds were of "not full penetration" type and it is expected that better fatigue results can be achieved if full penetration is allowed.

The fatigue results are given in figure 21

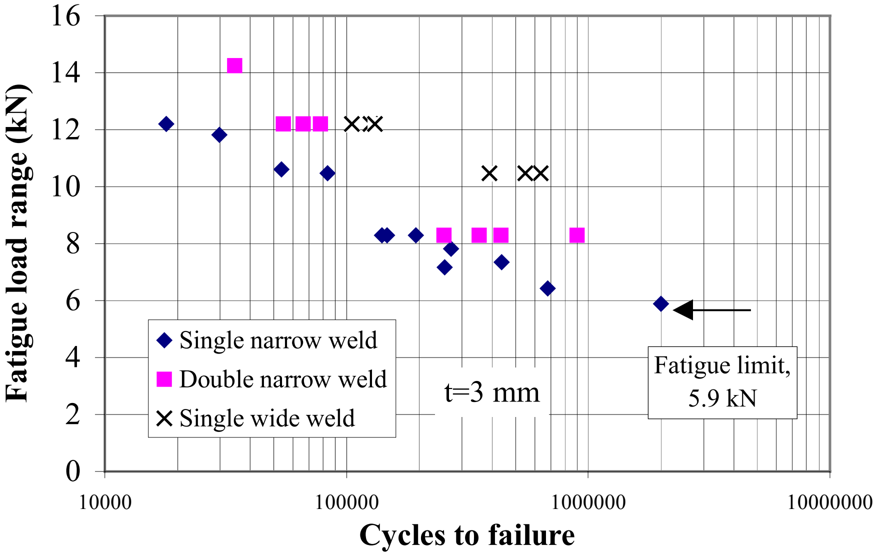


Figure 21 S-N curves for 3 mm laser welded simple lap shear joints. “Not full penetration”.

Although further testing is needed we can conclude that weld width is an important parameter for fatigue resistance. A comparison with results for spot welded joints (figure. 9) where the two somewhat stiffer specimens, 304:3/1 and 304:4/3, had fatigue limits of 3.01 and 3.75 kN indicate fatigue performance that are 2.5 to 3 times better for the laser welded joints.

Clinching (Pressjoining)

Within the automotive sector mechanical joining using 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 effect of typical stainless steel features as high strength, strong deformation hardening and high ductility have to be investigated to establish the limiting parameters for clinching of stainless steel.

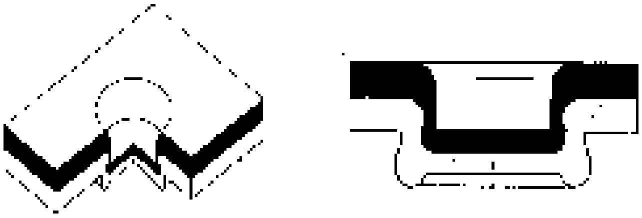


Figure 20 Perspective view and cross section of typical clinch element. R-Druckfügen (9).

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

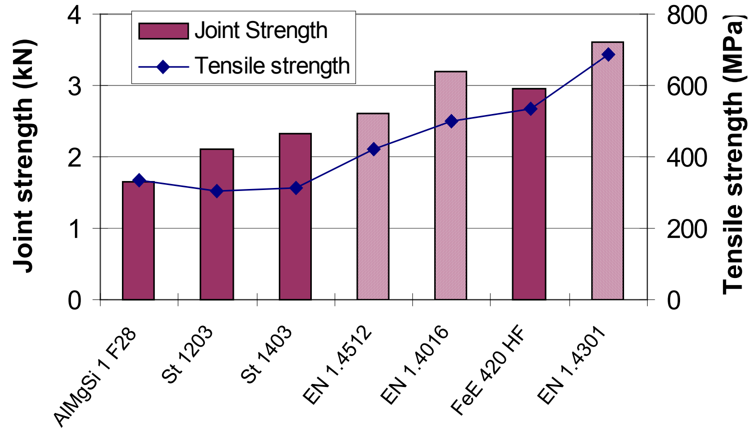


Figure 21 Clinch joint strength and tensile strength for different 1 mm sheet materials (9).

Fatigue properties of clinched stainless steel joints have been reported by J. Jacobsen (10). Non-penetrating, round clinches , as in figure 20, 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 EN 1.4301 and the more stable grade EN 1.4303 were tested. Results are given in figure 22.

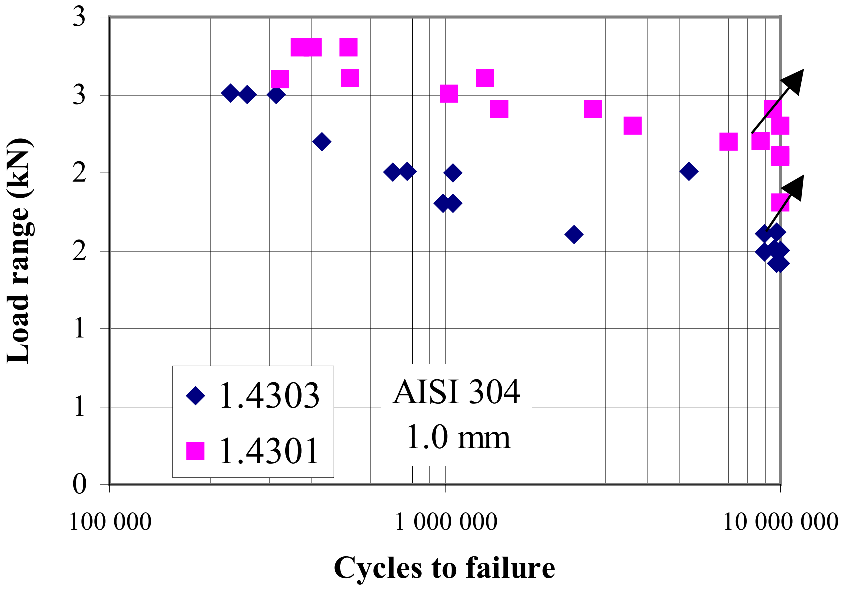


Figure 22 S-N curves for 1 mm clinched lap shear joints. Type R-DF/NH clinches.

The fatigue properties are similar to those for spot welded joints but since clinches can be set closer to each other than spot welds a multi-clinched joint is expected to have better fatigue properties than spot welded joints.

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 thickness' and with different types of specimens. One way of comparing is to give load ranges in "line load", e.g. the load divided by the specimen width. Such comparisons are made in figure 23 and 24.

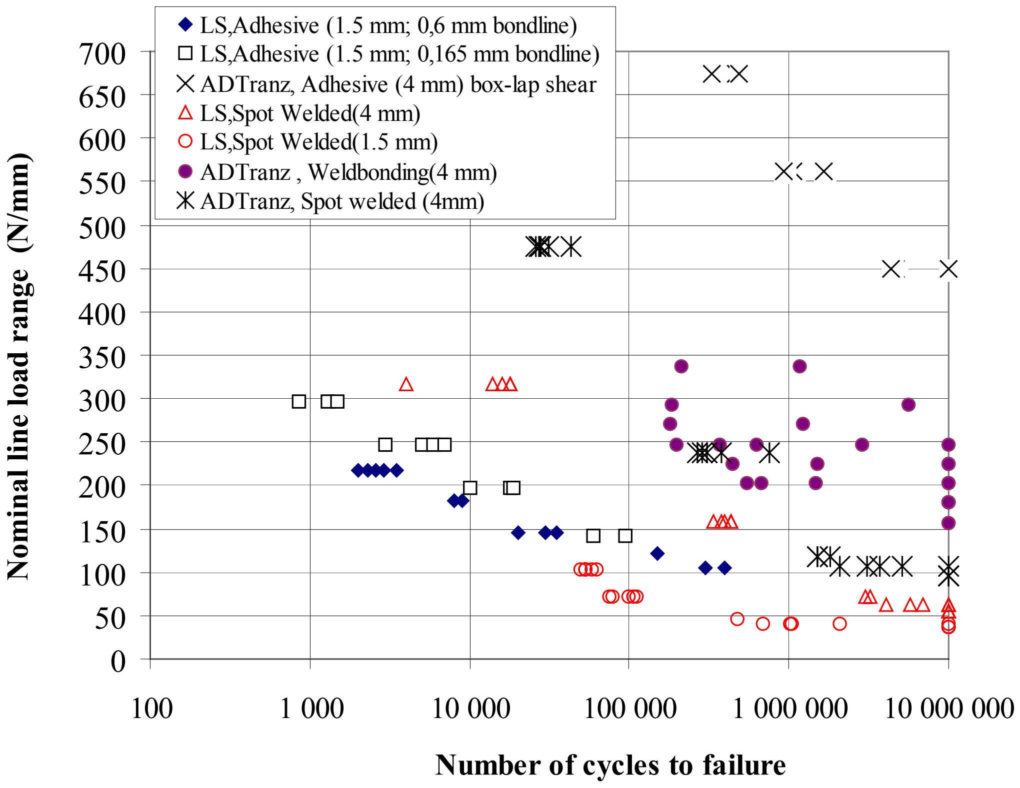


Figure 23 Line load range fatigue curves for spot welded, adhesive bonded and weldbonded lap joints.

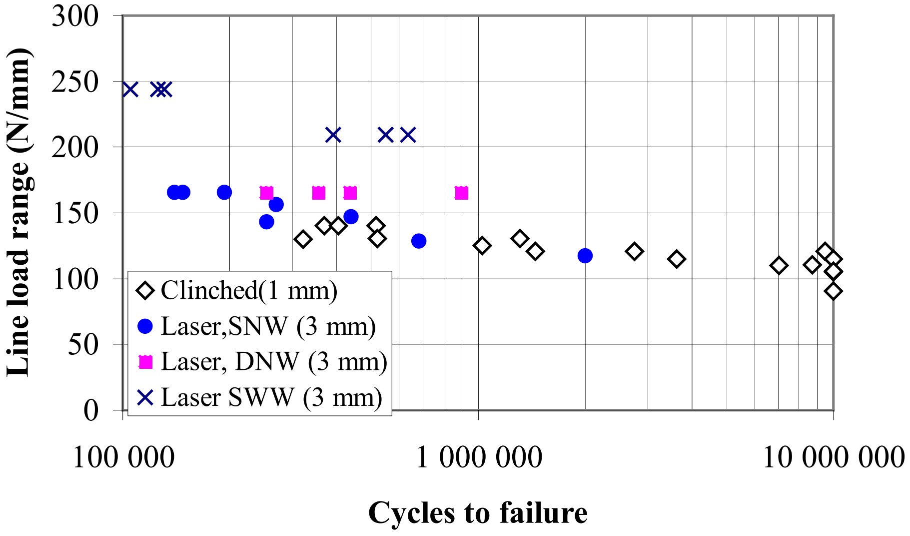


Figure 24 Line load range fatigue curves for clinched and lased welded lap joints.

The fatigue performance can be grade compared to spot welded joints as follows:

- ☐ Stiffer specimen have higher fatigue limits.
- ☐ Adhesive bonded joints show up to 5 times higher fatigue limit.
- ☐ Weldbonded joints have up to 2.5 times better fatigue limit , but show very high scatter.
- ☐ Laserwelded joints have substantially higher fatigue limit. Further testing is needed.
- ☐ Clinched joints have good properties primarily due to high clinch density.

CONCLUSIONS

- The important parameter for fatigue failure of spot welded joints, independent of specimen type (loading mode) and sheet thickness, is the stress concentration in the weld nugget described by the stress intensity factor range.
- Using adhesive bonding the surface condition of the adherend is important. However, the contribution to bond strength afforded by physical and/or chemical induced modifications are considered negligible. Simple alkaline degreasing or for special joints, shot blasting, are often sufficient.
- Weldbonding is shown to be possible but is questionable from a strength or fatigue strength point of view. If stresses over the strength of the spot welded joint are applied the over-all joint strength depends only on the adhesive bond. Since the strength of the weldbonded joint is lower than for a pure adhesive bonded joint it would then be better to use the latter.
- Laser welding of overlap joints is a very promising technique (but involves high investments and a risk for complicated systems for sheet handling).
- The understanding of overlap joining of stainless steel sheets is very different for different types of joining techniques. Spot welding is well understood and design techniques and rules are developed. Adhesive bonding and weld bonding is still in a developing phase but showing promising properties. Overlap laser welding and clinching are promising but are all but understood for stainless steel.

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