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Effect of grooves on adhesively bonded joints

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Abstract

Adhesively bonded joints are widely used in the aerospace and automotive industries in various structural systems: evidence of interface failure has been observed in many cases. The safety and reliability of these systems are dependent on the proper design of the constituent components. These components are often subjected to complex service loading conditions. However the failure mechanism is not well understood and considerable effort has been devoted to testing, theoretical prediction and numerical analysis to effectively address this issue. Adhesively bonded joints can provide an efficient method of joining that would be more extensively used if reliable methods of testing and analysis were available. The objective of this work was to study the influence of the macroscopic state of the substrate surface on the strength of adhesive joints. For that, several patterns were made on the surface of the substrates. The patterns were treated in two different ways, cleaned with acetone or chemically treated. The substrates were then bonded with two types of adhesive, a brittle one (AV138) and a ductile one (Araldite 2015) and static and fatigue tests were carried out. Static testing began by trying to determine which depth of the pattern allowed better results for the joint strength of both adhesives. The next step was to test the different patterns with the depth chosen to see which was the best. The different patterns were always compared with specimens without pattern. For the fatigue tests, the pattern and adhesive with the most interesting results were used. After analyzing the results, it was observed that the patterns can increase the joint strength of non treated substrates in the case of the brittle adhesive.

Keywords: Adhesive, Lap joint, Shear strength, Brittle

1. Introduction

In this work, single lap joints were studied. This type of joint is the most studied in the literature, where there is multiple simple criteria of dimensioning. The resistance of the joint depends on several factors that are hard to quantify, like the length of overlap, the plasticity of the adhesive, the thickness of the adhesive and the surface treatment. From the beginning of the 20th century to the current 21st century, a progressive utilization of adhesives in bonding can be noticed. Adhesives are progressively replacing the conventional mechanical fastening systems. Currently, structural adhesive bonding is more used, replacing or used in conjunction with the conventional mechanical fastening systems, with numerous advantages over them. Some of the characteristics of the structural adhesives are [1].

- A more uniform stress distribution through the connected area,which allows for greater stiffness and load transfer.
- Improved fatigue strength in adhesively bonded joints ;
- Weight reduction and a lower cost;
- Connection of different materials in composition and with different coefficients of
- expansion;

- Usually adhesives are the most convenient and effective method to connect two
- materials;
- Can make the project more flexible allowing the use of new concepts and materials;
- Creates a continuous contact between the connected surfaces.

Although adhesives have a number of advantages, it is necessary to take into account the limitations they have

- Design connections that eliminate peel, cleavage and impact loads.
- Avoid localized stress and ensure an even distribution of stress by subjecting the adhesive to shear stress.
- To obtain good results, a careful surface preparation is required.
- Quality and security controls are hard to do.
- Adhesives have limited resistance to extreme conditions, such as heat and humidity due to the polymer nature of the adhesive.

Adhesive joints are increasingly being used in industrial applications, hence the need for a more detailed analysis of the structures. This analysis involves a choice of the most appropriate joint geometry, the adhesives and the construction of the adhesive joints. These choices are based on environmental conditions, loads and the work to which the joint is subjected. The factors to consider are: the yield of the substrate and its thickness, type and thickness of the adhesive, the length of overlap and the surface treatment. In single lap joints, the edges of the joint are the areas that have the highest stress concentration. The average stress is lower than the stress on the edges of the joint, and this uneven distribution of stress along the adhesive layer leads to failure normally for loads of inferior value than the adhesive can support [2].

Figure 1 shows the difference in joint strength for ductile and brittle adhesives, depending on the length of overlap. The joint strength increases initially, being higher for brittle adhesives. But for big overlaps, it appears that the ductile adhesives have joint strength much higher than the brittle adhesives [3].

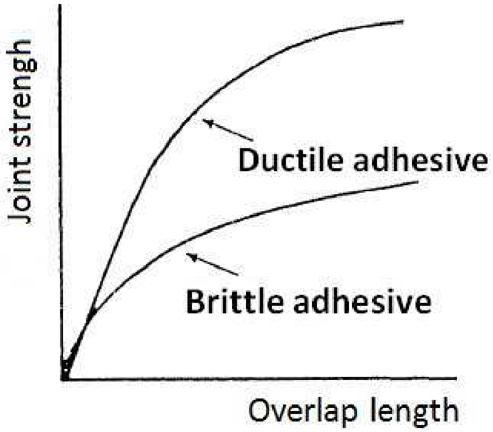

Figure 1: Effect of overlap length on rupture strength for ductile and brittle adhesives [4]

Figure 2 shows, for a single lap joint, the difference of the shear stress distribution in a joint with a brittle adhesive and a ductile adhesive. It is evident that there is a high stress at the ends of the joint for the brittle adhesive and a greater uniformity of stress along the joint for the ductile adhesive. The ductile adhesive can take advantage of all of the overlap length, unlike the brittle adhesive, which explains why the rupture strength increases almost linearly with the length of overlap in the case of ductile adhesives.

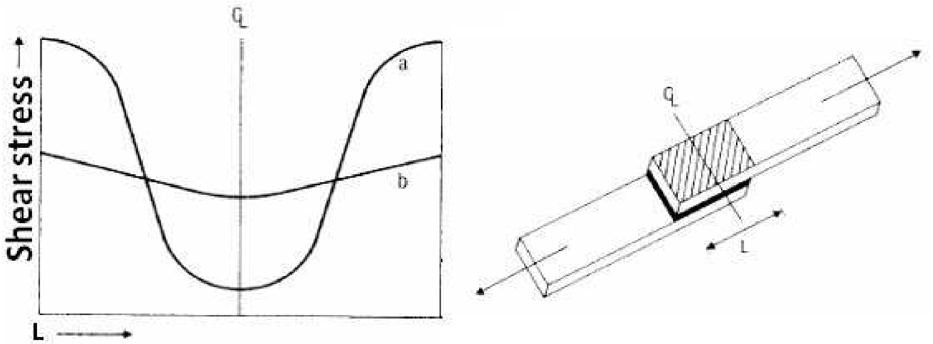

Figure 6: Difference in stress distribution along the overlap for a single lap joint. a) Brittle adhesive, b) Ductile adhesive [5]

The thickness of the adhesive layer is an important factor when it comes to structural adhesives. An optimum thickness should be ensured for the adhesive to be able to obtain the best performance of the joint. The thicknesses commonly used and recommended by the manufacturers are between 0.1 and 0.2 mm. It is experimentally verified that the resistance of a joint decreases with an increase of adhesive thickness from 0.1 – 0.2 mm. For thickness less than 0.1 mm, there is a sudden drop in resistance of the joint, possibly due to the fact that there is a risk of failure of bonding [1].

The decrease of joint strength with the increase of thickness can be explained by several parts:

1. For high adhesive thickness, there is the risk of introducing defects in the joint, such as air bubbles and micro cracks;
2. At the extremities of the joint, the bending moment increases (depending on the thickness of the adhesive and the substrate), resulting in a decrease in the resistance of the joint;
3. Plastification in the case of ductile adhesives occurs for higher loads in high thickness joints, but spreads more rapidly along the overlap resulting in a lower resistance of the joint.

The surface treatments are intended to form surfaces which are resistant and easy to wet. The strength of an adhesive joint increases significantly when loose particles such as corrosion products, paint and other contaminants are removed from the surface. Roughness is a parameter which affects the strength of bonded joints, because it leads to an increased contact area between the two substrates and increases the interface connections. The substrates must present, in the area of overlap, an intermediate roughness so that the entrapment of air in the joint interface does not happen. A high surface roughness may cause an increase of stress concentration and consequent decrease in the resistance of the joint because the adhesive does not fully penetrate into the cavities. For metals, roughness may increase the resistance of the joint but for substrates with a low surface energy the increase of roughness does not have the same effect, as shown by **Pinto et al** . Figure 3 shows the phenomenon of non-penetration of the adhesive in the cavities of the substrate.

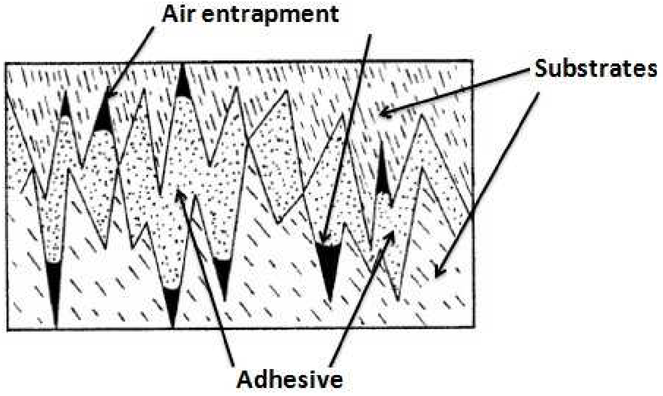

Figure 7: Representation of possible defects on surfaces with high roughness

2. Experimental Details

An experimental study was planned to determine the influence of the surface pattern on the resistance of single lap joints. The experiments consisted in static and fatigue tests for various specimens with different patterns. The rupture strength of the specimens was compared along with the behavior of the specimens under cyclic loads and conclusions were drawn.

2.1 Adhesive Description

For the testing program two different kinds of adhesives were selected. A brittle one (Huntsman AV138) and a more ductile one (Huntsman Araldite 2015). These adhesives when applied on a patterned surface are expected to have different behaviors. The brittle adhesive, Araldite AV138 with Hardener HV998 is a two component, room temperature curing paste adhesive of high strength. When fully cured the adhesive will have a excellent performance at elevated temperatures (120 ºC) and has high chemical resistance. It is suitable for bonding a wide variety of metals and is widely used in many industrial applications where resistance to aggressive or warm environments is required. The resin and hardener should be mixed with a mass relation of 100/40 (resin/hardener) until they form a homogenous mix. The mechanical properties of the adhesive can be seen on Table 1.

Table 1: Mechanical Properties of AV138 adhesive [11]

Shear Modulus G (MPa)	1559 ± 11
Shear Yield Stress,ϑ (Mpa)	25.0 ± 0.55
Shear strength, ϑr (Mpa)	30.2 ± 0.40
Shear failure strain,((%)	5.50 ± 0.44

The ductile adhesive, Araldite 2015 is a two component, room temperature curing paste adhesive giving a resilient bond. It is thixotropic and non sagging up to 10 mm thickness and has a high shear and peel strength. The mechanical properties of the adhesive can be seen on Table 2.

Table 2: Mechanical properties of Araldite 2015 adhesive [11]

Shear Modulus G (MPa)	487 ± 77
Shear Yield Stress,ϑ (Mpa)	17.9 ± 1.8
Shear strength, ϑr (Mpa)	17.9 ± 1.8
Shear failure strain,(f (%)	43.9 ± 3.4

2.2 Substrate material

The material used for the substrates was AA6082-T6 aluminium. This choice was made because the aluminium due to its low weight and good mechanical properties is an increasingly used material in aerospace and automotive industries which are among those that use adhesive techniques. Aluminium also helps to keep costs down in the fabrication of the specimens because it is easier to do the patterns. The mechanical properties of the aluminium can be seen in Table 3.

Table 3: Mechanical properties of aluminium AA6082-T6 [12]

Tensile strength (MPa)	305.6
Yield Stress (MPa)	245.1
Elongation at failure (MPa)	16.5

Young’s Modulus, E (GPa)	69.5
Shear Modulus,G (Gpa)	25.34
Poisson’s Ratio	0.346

2.2 Surface Patterning

The preparation of the surface of the substrate is of extreme importance in the implementation of a glued joint, as its resistance depends heavily on the quality of this operation. In an ideal bond, the substrate must be the weakest link, however in most of the bonded joints it is the adhesive that behaves as the weakest link. Different surface patterns and depths were tested in tensile tests for both adhesives and the best pattern and depth were then selected for the fatigue tests. Figure 8 shows the different patterns that were used and the unprepared surface used for comparison.

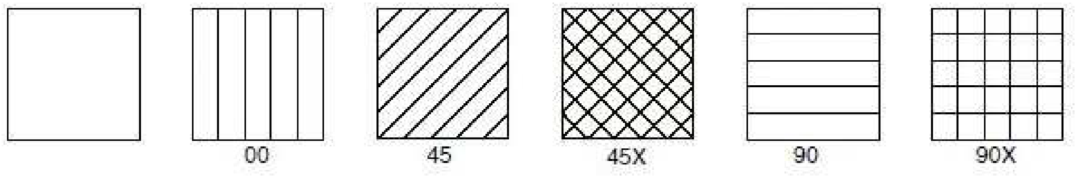

Figure 8: Surface preparation pattern used and their designation

2.3 Surface Treatments

The effect of the grooves was assessed under two conditions: with and without surface treatment. The idea was to check if the grooves would be sufficient to have a good strength without additional treatment. For the case of ‘no treatment’ only acetone was used to clean the substrates after the grooves were done. In the case of surface treatment, a chemical surface treatment using chromic acid was chosen as it is verified that the tensile strength of chemically prepared specimens is significantly higher than without preparation. It should, however, be noted that this process is currently being phased out of industrial applications. Despite being a very efficient procedure, it uses a large amount of toxic and even carcinogenic chemicals. Some alternative procedures are being currently developed which are much less damaging to the environment. As an example, the work of **G. W. Critchlow** [14] studied several duplex oxide layer mechanisms to substitute anodizing with chromic acid. Various non toxic-electrolytes have been tested [13].

The chromic acid used for this work was produced with the following composition:

- 1 liter of distilled water
- 300 gm of H_2SO_4
- 60 gm of $Na_2Cr_2O_7.H_2O$

The procedure for the preparation of the specimens is described below:

1. 300g of high grade sulphuric acid are dissolved in 1 liter of distilled water.
2. The $Na_2Cr_2O_7.H_2O$ crystals are dissolved in the solution. This reaction is exothermic and heats the recipient. The operation must be done in a ventilated area and the recipient must have a large open section to minimize the chances of overheating.
3. The specimens are suspended on metallic wires with half of their length submerged in the chromic acid solution.
4. The solution is heated up to 65ºC and kept at that temperature for 15 minutes.
5. The specimens are removed and quickly rinsed with tap water. A second rinse is performed with distilled water to remove surface contaminants.
6. The specimens are then dried in hot air and carefully conditioned to avoid the reappearance of oxides.

The final result is a very clear surface, clearly devoid of any contamination. The application of the adhesive has to be fast to avoid the reappearance of oxides.

2.4 Bonding

The steps necessary to prepare the specimens are the following:

1. Heat the tools to 80ºC for easier application of the mould release agent.
2. Apply the mould release agent on the mould and spacers.
3. Apply a thin adhesive layer on the overlap being careful so that no air is trapped inside.
4. Mount the mould.
5. Insert the mould into the previously heated at 40ºC hydraulic press.
6. Cure the adhesive at 100ºC and with a load of 2000 lbs for 1h30.

2.5 Static Testing

The tensile test of a single lap joint is one of the most common methods to characterize an adhesive joint. The test consists in applying forces in the longitudinal direction of the specimens until the occurrence of rupture. As can be seen by the geometry of the specimen (Figure 22), there is a misalignment of traction forces, even when spacers are used in the places of mooring. The test of a single lap joint can be used as a method for comparative study of adhesives, provided that the standardization of other parameters that can affect the Oucome of the tests is ensured. The tests were done on a MTS 810 machine with a test velocity of 1 mm/min in typical laboratory ambient conditions (approximately 25ºC and 50% relative humidity).

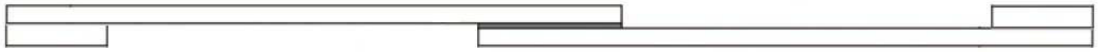

Figure 9 Representation of a single lap joint

2.6 Fatigue Testing

The effect of the grooves might be different under cyclic loads. The grooves act like stress concentrators which may lead to a shorter life of the specimens under cyclic loads. The behavior under cyclic conditions is a function of the type of adhesive and, above all, the geometry of the joint. Usually, the tests that are performed have as an objective to represent a diagram of maximum stress vs number of cycles for rupture. This diagram is called the SN curve or Wöhler curve. The solicitation frequency has an important role in fatigue behavior.
The maximum usable frequency is dependent on the thermal conductivity of the par adhesive/substrate, the method of loading and the size of the specimen. The fixation of the specimens must keep the specimens well aligned so that there is no deviation in the applied force of more than 2%. The tests were done on a MTS 810 machine with a test frequency of 10 Hz to see the effect of grooves under cyclic loads. Three levels of load were used (80%, 60% and 40% of the ultimate load obtained in the static test) and the maximum number of Cycles that a specimen could do was set to one million cycles. Three specimens were tested for each load level.

3 Results

3.1 Influence of Pattern Depth

3.1.1 Adhesive 138

Tensile tests were performed in order to see the influence of the depth of the patterns. In these tests the patterns were applied at 90º with depths of 0.1 and 0.3 mm. 0.1 mm is the smallest dimension possible to machine on the available equipment and 0.3 mm represents 10% of the substrate thickness, reducing the resistance of the substrate considerably. Four tensile tests were done for each depth and 4 not patterned specimens were also tested. This was done for both surface treatments. The first tests were done with the specimens only cleaned with acetone. This should lead to weaker joint strength than the specimens that were chemically treated, which should simplify the identification of the best surface pattern depth. The next step was to test chemically treated specimens. The same number of specimens for the different depths was tested in addition to the specimens with no pattern.

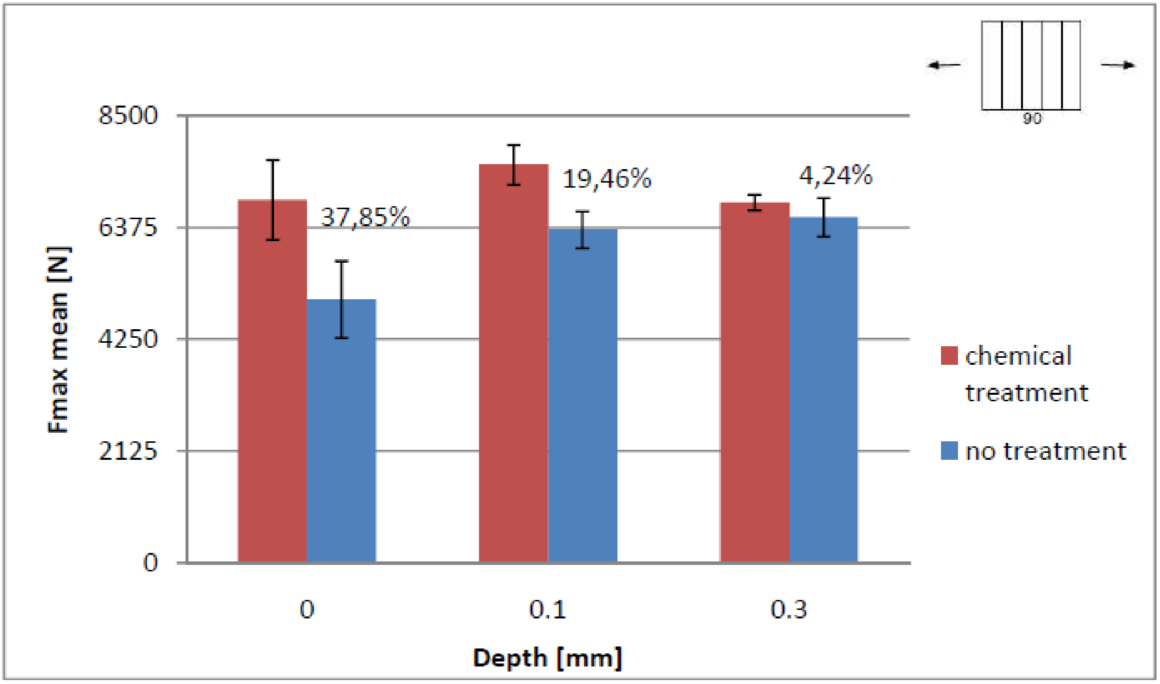

Figure 10 AV138 with and without chemical surface preparation (the values in percentage represent the increase in joint strength from 'no treatment' to 'chemical treatment')

With chemically treated specimens, the results show that the pattern with a depth of 0.1 mm has the best result. The specimen with no pattern has a high increase of strength inrelation to no treatment while the pattern with a depth of 0.1 mm has a lower but still considerable increase of strength. The increase of strength from the no treated surface to thetreated surface is because the failure goes from mixed cohesive/adhesive to cohesive. The 0.3 mm pattern presents very similar results with or without chemical treatment. The results may be influenced by an equilibrium between the anchoring effect and stress concentration factors.

3.1.2 Adhesive Araldite 2015

The first tests were done with the specimens only cleaned with acetone. This should lead to weaker joint strength than the specimens that were chemically treated, which should simplify the identification of the best surface pattern depth. The tests show that the patterned surface leads to a lower resistance of the joint, but no conclusion can be made in relation to the different depths since the results are very similar between them and the test uncertainty, defined by the standard deviation of the results overlaps the mean values.

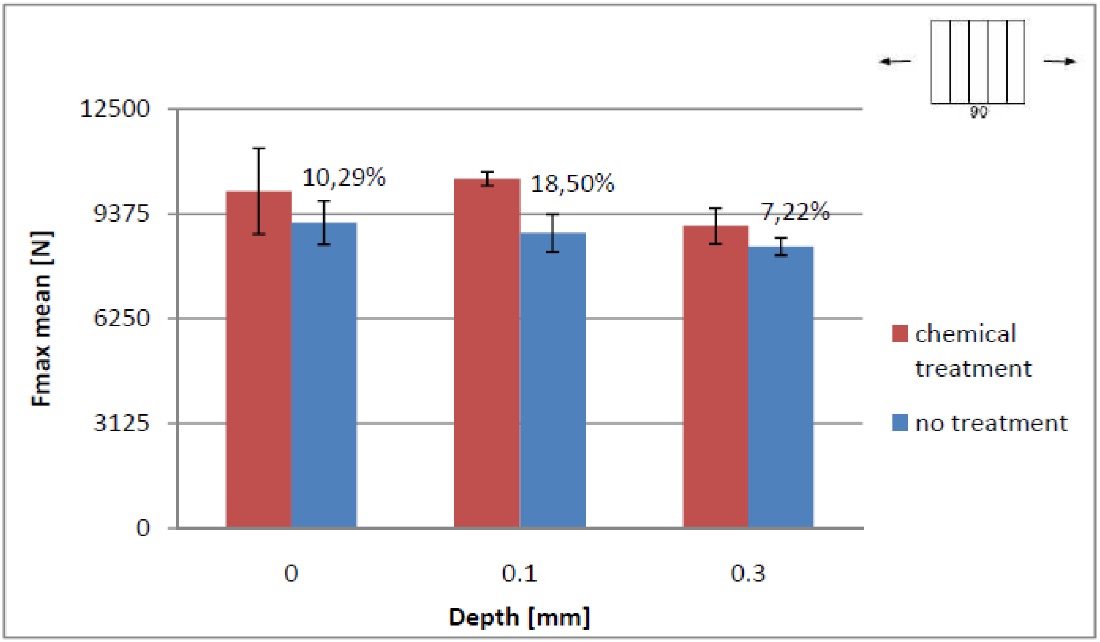

Figure 11 Araldite 2015 with and without chemical surface preparation (the values in percentage represent the increase in joint strength from 'no treatment' to 'chemical treatment')

With chemical treated specimens, the results show that the pattern with a depth of 0.1 mm has the best result. The specimen with no pattern has an increase of strength smaller than the pattern with a depth of 0.1 mm in relation to the no treatment surface. The 0.3 mm depth pattern presents very similar results with or without chemical treatment. Because of the results of the patterns with a depth of 0.3 mm, this depth was not used again in the following tensile and fatigue tests. Figure 12 shows a typical load displacement curve. The curve is linear up to failure which shows that there was not any adherend plastic deformation during the test.

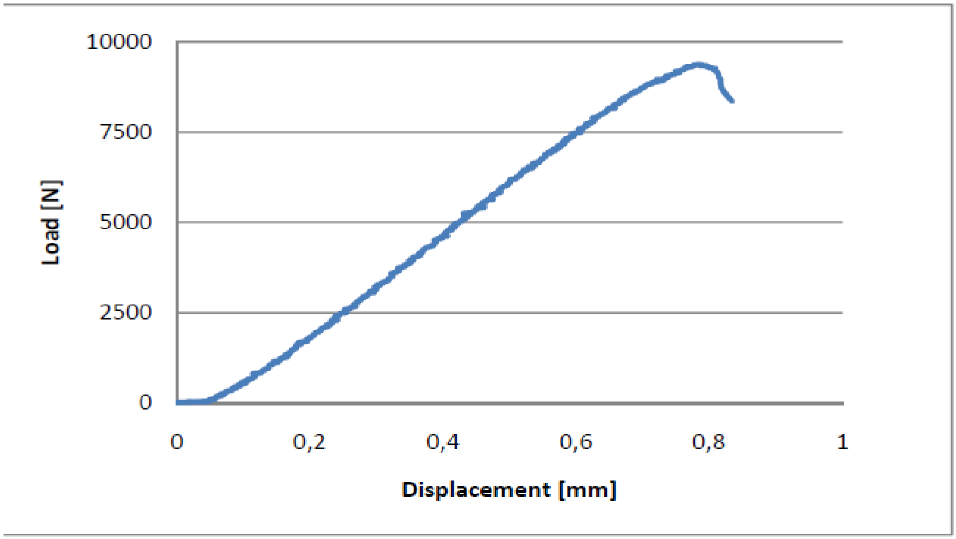

Figure 12 Typical load displacement curve

3.2 Influence of the pattern direction

3.2.1 Adhesive AV138

The first tests were done with the specimens only cleaned with acetone. This should lead to weaker joint strength than the specimens that were chemically treated, which should simplify the identification of the best surface pattern. The tests show that the best results were obtained with the crossed patterns at 45º and 90º.
This may be related to the bigger anchoring effect of these patterns due to the higher affected area. The patterns at 45º and 90º also had good results almost to the level of the crossed patterns at 45º and 90º. The test uncertainty, defined by the standard deviation of the results of each specimen is high. The next step was to test chemically treated specimens. The same number of specimens for the different patterns was tested. The results are presented in Figure 13.

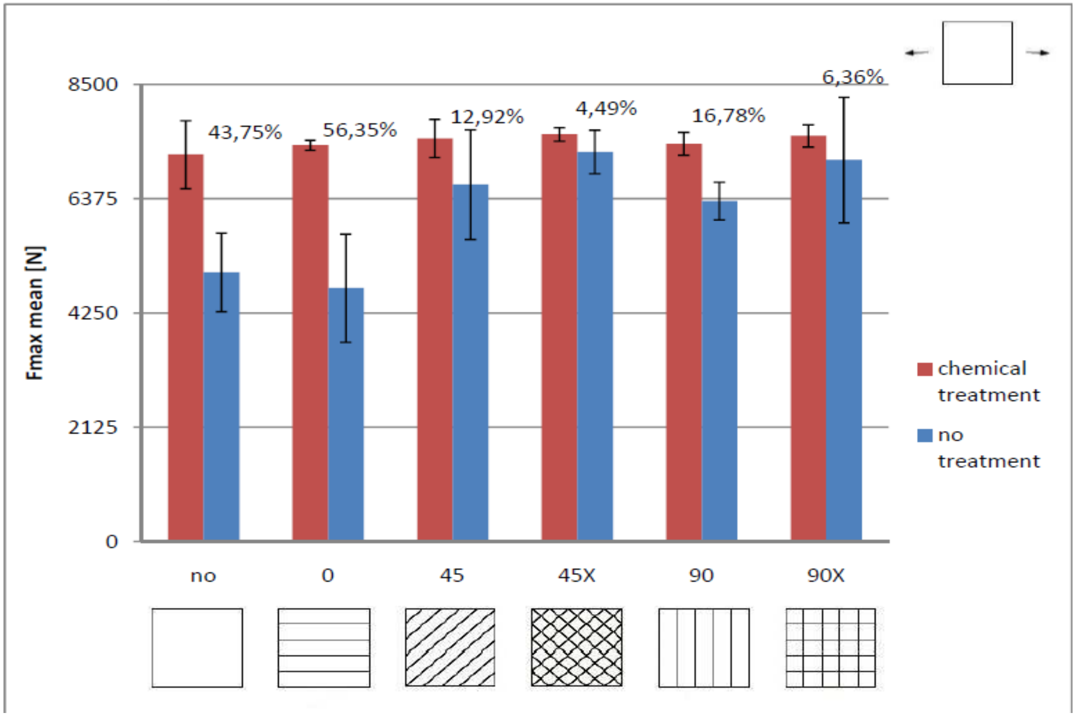

Figure 13 Various surface patterns with a depth of 0.1 mm with and without chemical surface preparation bonded with AV138 (the values in percentage represent the increase in joint strength from ‘no treatment’ to ‘chemical treatment’)

The tests show that the results are all very similar between the patterns with the test uncertainty, defined by the standard deviation of the results of each specimen overlapping the mean values. The specimens that were chemically treated present higher rupture strength than the non chemically treated, but are not sensitive to the presence of the patterns since the results are similar between the patterns. The fracture surfaces show that all chemically treated specimens had cohesive ruptures. The chemical treatment allows the specimens to achieve higher rupture strengths but presents an indifference to the presence of patterns while with no chemical treatment the presence of patterns clearly had an effect of the rupture strength of the specimens.

3.2.2 Adhesive Araldite 2015

The first tests were done with the specimens only cleaned with acetone. This should lead to weaker joint strength than the specimens that were chemically treated, which should simplify the identification of the best surface pattern. The next step was to test chemically treated specimens. The same number of specimens for the different patterns was tested. The results are presented in Figure 14. The tests show that the results are all very similar between the patterns with the test uncertainty, defined by the standard deviation of the results of each specimen overlapping the mean values. The results between the chemically treated specimens and the non treated were very similar.

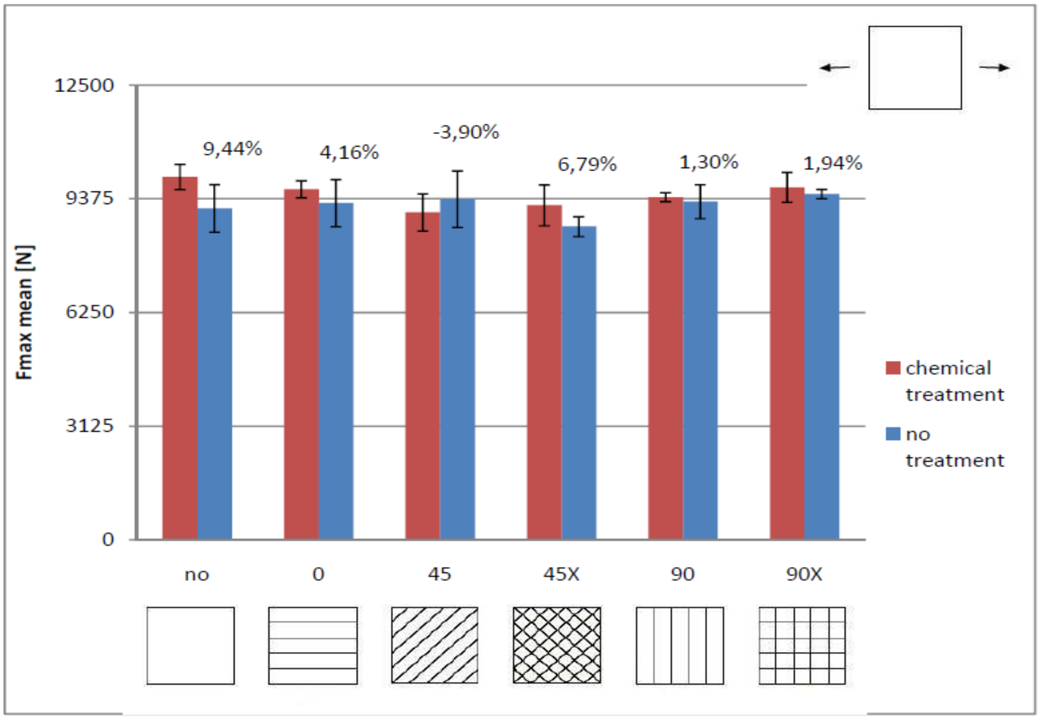

Figure 14 Various surface patterns with a depth of 0.1 mm with and without chemical surface preparation bonded with Araldite 2015 (the values in percentage represent the increase in joint strength from 'no treatment' to 'chemical treatment')

3.3 Fatigue testing

For fatigue testing, only two types of specimens were used: no pattern and a 90º pattern with a depth of 0.1 mm. The 90º pattern was not the best overall but showed good results and it is easier to manufacture than the other patterns presenting savings in time and costs. The adhesive AV138 was the only one tested because adhesive Araldite 2015 did not show any sensitivity to the patterns. Three fatigue tests were done for each load level for both patterns.

3.3.1 Adhesive AV138

The first tests were done with the specimens only cleaned with acetone. The results are presented in Figures 15 and 16. In Figure 41 the load is normalized in relation to the static failure load.

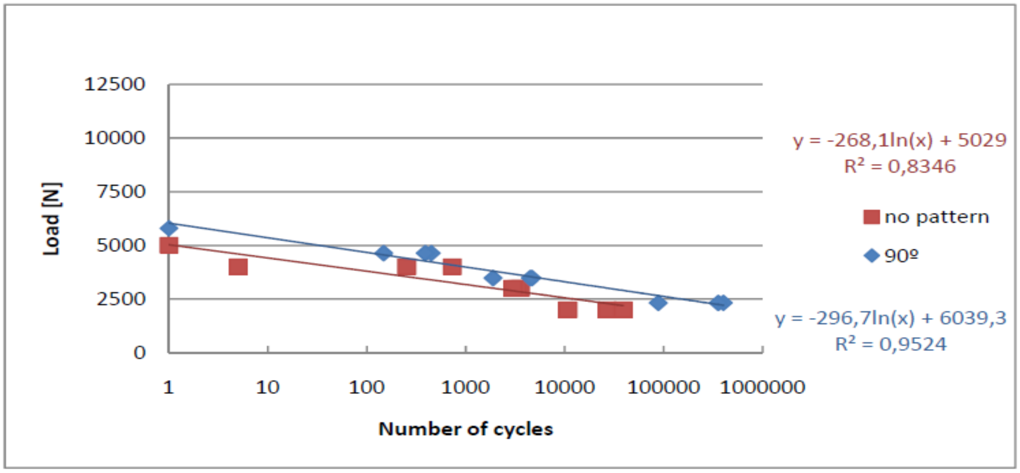

Figure 15 Fatigue results for specimens with no pattern and 90º pattern bonded with AV138 and no surface treatment

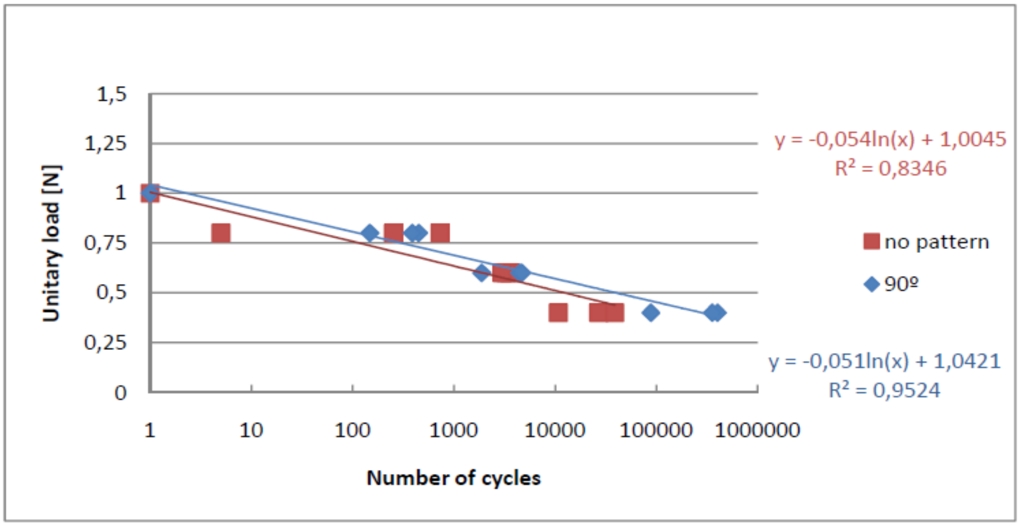

Figure 16 Fatigue results with unitary loads for specimens with no pattern and 90º pattern bonded with AV138 and no surface treatment

The tests show that the patterned specimens were better than the specimens with no pattern. At 40% of the ultimate load, the patterned specimens were close to 500.000 cycleswhile the specimens with no pattern at the same level were only close to 50.000 cycles. The slope of the patterned specimens is lower than that of the specimens with no pattern. This shows that the grooves have a good effect on the behavior of the specimens under cyclic conditions The next step was to test chemically treated specimens. The results are presented in Figures 17 and 18. In Figure 18 the load is normalized in relation to the static failure load.

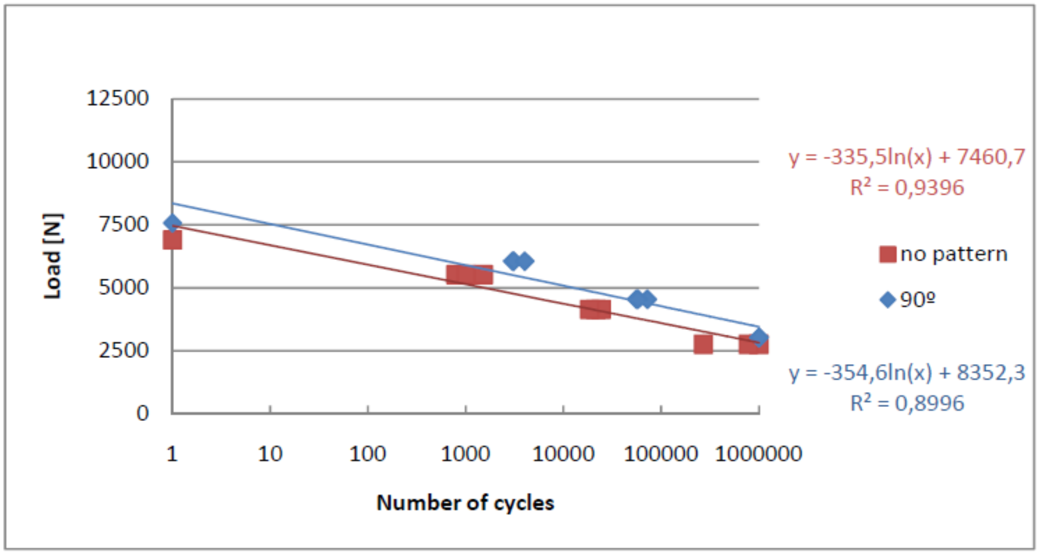

Figure 17 Fatigue results for specimens with no pattern and 90º pattern bonded with AV138 and chemically treated

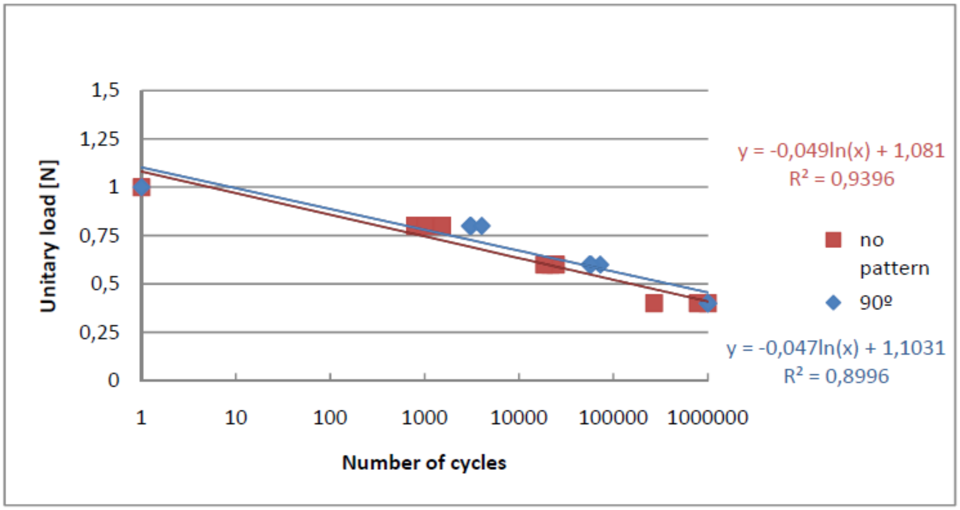

Figure 18 Fatigue results with unitary loads for specimens with no pattern and 90º pattern bonded with AV138 and chemically treated.

The tests show that the patterned specimens were slightly better than the specimens with no pattern. All the patterned specimens achieved 1,000,000 cycles with a load of 3621 N while only one of the specimens with no pattern achieved 1,000,000 cycles with a load of\ 2761 N. The slope of the patterned specimens is also slightly lower than that of the specimens with no pattern. This shows that the grooves have a good effect on the behavior of the specimens under cyclic conditions.

4 Conclusions

Single lap joints with patterns were studied with and without surface treatment and bonded with a brittle and a ductile adhesive. The conclusions that can be taken from the study are:

1. Tensile testing showed that the depth of the patterns that showed the best results was 0.1 mm for both adhesives.

2. Tensile testing with the brittle adhesive (AV138) shows that the surface patterns influence the joint strength. This influence is most noticed for the specimens with no surface treatment, with the patterned specimens having a higher strength than the specimens with no pattern. With the chemically treated specimens, the patterns still have a influence on the joint strength but that influence is considerably smaller compared with the specimens that were not treated.
3. Tensile testing with the ductile adhesive (Araldite 2015) shows that the surface patterns does not have a significant influence on the joint strength.
4. Fatigue testing with the brittle adhesive (AV138) shows that the surface patterns have a good effect on the behavior of the specimens under cyclic conditions. The patterned specimens consistently endured more cycles than the specimens with no pattern. This happened especially with the specimens without surface treatment.
5. The surface patterns with no treatment are a good alternative to the chemical surface treatment using chromic acid.

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