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Experimental Study of the Impact of Notches Made in the Front Edge of Adherends on the Properties of Static and Fatigue Strength of Adhesive Joints

Andrzej Kubit[1,*], Władysław Zielecki[1], Wojciech Berezowski[2], Ryszard Perłowski[1], Katarzyna Łabno[3], Tomáš Katrňák[4]

[1] Department of Manufacturing and Production Engineering, Rzeszow University of Technology, al. Powst. Warszawy 8, 35-959 Rzeszów, Poland
[2] Department of Automation and Robotics, State University of Applied Sciences in Krosno, Rynek 1, 38–400 Krosno, Poland
[3] Grupa Azoty, ul. Kwiatkowskiego 8, 33-101 Tarnów, Poland
[4] Institute of Aerospace Engineering, Brno University of Technology, Antonínská 548/1, 601 90 Brno, Czech Republic

Abstract: This paper presents the effect of simple structural changes consisting in making notches on the edge of adherends on the static and fatigue properties of adhesive joints. The study is based on the set of experimental static strength tests of the single lap shear adhesive joints. It has been shown that a slight increase in load capacity is possible by using adhesive-filled notches. However, this structural modification leads to an increase in the standard deviation of test results. Based on the fatigue strength tests done at the limit number of cycles equal to 2×10^6, it was shown that the use of notches on the front edge of adherends, which are filled with adhesive, can significantly increase the fatigue lifetime of the joint. The effect is shown in the area of low-cycle fatigue, where for fatigue stress with a maximum value of 11.5 MPa, an increase in the average value of fatigue lifetime by 481.5% was shown for joints with notches. On the basis of fractography analyses using SEM microscopy, it was shown that the positive effect of the notches is caused by the absorption of some energy by the adhesive filling the notches, due to the increased susceptibility of the adhesive in this area to elastic deformations.

Keywords: Adhesion; adhesive joints; fatigue strength; high cycle fatigue; S–N curves

1. Introduction

Adhesive joints are widely used in various industrial sectors, such as aerospace and automotive, where distributed loads can be transferred between joined adherends. Adhesive joints are crucial mainly in cases where is difficult or even impossible to use other types of joining elements by means of fastener joining, riveting or welding [1, 2]. Although, there are a number of advantages, the considered adhesive joints are characterized by relatively low strength compared to typical welded or mechanical joints. [3]. For example, when joining very thin materials. Another example may be the combination of such materials that are not suitable for welding due to structure and weakening under the effect of heat [4-6]. Good damping properties of the adhesive joint can also be considered as an advantage [7].

The literature review shows the strength of adhesive joints is affected by many construction factors. One of them is the length of the overlap [8, 9]. The study [8] presents the performed stress analysis to compare different joint geometries. As part of this work, it was found that the optimal type of joint is highly dependent on the type

*** Corresponding author:** Andrzej Kubit, ***E-mail address:*** *akubit@prz.edu.pl*

of adhesive used, so that less strong and ductile adhesives are more suitable for joint geometries that exhibit large stress variations. In addition, it has been shown that the length of the overlap above a given value does not result in an increase in strength.

Authors of the papers [10-14] present the results of tests on the thickness of adherends. With certain properties of adhesives and load conditions, the strength of the joint increases with the increase in the thickness of the adherends. This is due to the stress distribution in the adhesive joint, because with thin adherends a complex state of stress usually occurs. On the other hand, the higher the thickness of the adherends is, the stiffness increases due to dominant shear stresses in the properly designed shear lap joints.

The strength tests of the overlapping adhesive joint conducted by the authors [15] showed an increase in strength with the increase in the length of the shoreline. This effect should be associated with the existence of a flash on the edge of the adhesive, which increases the contact surface. Numerical analysis using FEM have shown that the effect of increasing the breaking stress along with the increase in the length of the edge line is also affected by the decrease in the stress at the ends of the overlap.

Reducing the maximum stresses at the ends of the adhesive joint and increasing the strength of the joints can be achieved by beveling the edges of the joined elements. Based on research by Durodol [16] the assumption can be concluded that the beveling of the overlap ends has a positive effect, regardless of the thickness of the joined materials. The author also shows that reducing the bevel angle increases the strength of such a joint.

The authors of paper [17] conducted FEM numerical analyses for a shear-loaded lap joint. The analyses concern the effect of the value of the face angle of the adherends on the distribution of shear and normal stresses in a single-lap joint of elements of different thickness. With the proposed modifications, benefits were observed related not only to the reduction of the maximum values of shear and normal stresses, but also to the averaging of the distribution in the zone of their joint.

Similar analyses were done by the authors of [18], who supported these considerations with experimental research. They confirm the possibility of improving the strength of overlapping adhesive joints with structural modifications. In the variant with chamfer, an increase in shear strength of about 20% was obtained [18].

In the work [19], structural modifications consisting in making a radius in the edge zones of the joint were considered. Considerations from publication [19] also apply to a lap joint subjected to shear. Different dimensions of the radius were considered here, as well as adhesives with different modulus of elasticity. The best variants showed an increase in shear strength of about 40%.

The structural modification, i.e. making a radius in the edge zone of the adherend, seems to be right in the context of fatigue strength, because it avoids sharp edges that are stress concentrators.

With many advantages, one of the significant disadvantages of adhesive joined structures is their relatively low durability and fatigue strength compared to other joining technologies [20-22]. Therefore, equal methods to improve fatigue lifetime are important. One of the important directions of improving the fatigue properties of adhesive joints is modifying construction adhesives with nanofillers [23]. Kubit et al. [24] also shows the possibility of improving the tear strength by locally increasing the adhesive layer at the edge of the adherend.

In this work, experimental studies were done to analyze the effect of notches on the front edge of the adherends on the properties of static and fatigue strength. A comparison of the fatigue curves for the variant 2 with the modification in the form of notches filled with adhesive and the base joint variant 1 was made. Fractography analyses were performed with selected joints damaged both in terms of low and high-cycle fatigue.

2. Materials and methods

The tests of the effect of notches on the front edge of the adherends on the properties of static and fatigue strength were done for single lap joints with the dimensions shown in Figure 1. Both adherends were made of S235JR steel sheet.

The joints were made using epoxy adhesive Araldite 2024-2. Immediately before the preparation of adhesive joints, the sheet surfaces were sandblasted using Aloxite 95A, which contains 96% aluminium oxide (Al_2O_3), ~3% titanium dioxide (TiO_2) and 1-2% other admixtures. Abrasive blasting was performed under the following conditions: grain size a = 0.27 mm, air pressure p = (0.8 ± 0.1) MPa, and blasting time t = 60 s. The hardening process of the adhesive was conducted under the following conditions: time t = 24 h; room temperature (20 ± 3 °C); constant pressure of 0.1 MPa applied to the joint area.

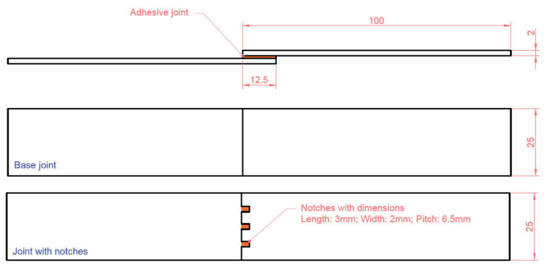

Figure 1: Geometry specification of specimen variants for the static and fatigue tests (dimensions are in millimeters).

Investigation of the static load capacity of the joint by shear tests was performed at ZWICK/Roell Z-100 universal testing machine. The tests were done with the use of the crosshead speed of 5 mm/min at ambient temperature. The specimen set V1S1 consists of five specimens of variant 1 and they were marked V1S1-1, V1S1-2, V1S1-3, V1S1-4 and V1S1-5. The following set V2S1 of variant 2 includes specimens V2S1-1, V2S1-2, V2S1-3, V2S1-4 and V2S1-5. Each specimen was marked with the specimen number on both ends for the direct identification before and after the test.

High-cycle fatigue strength tests were performed at the limit number of cycles equal to 2×10^6. The tests were done at a hydraulic fatigue machine HT-9711 Dynamic Testing Machine. The setup for fatigue strength tests with the mounted specimen is shown in Figure 2.

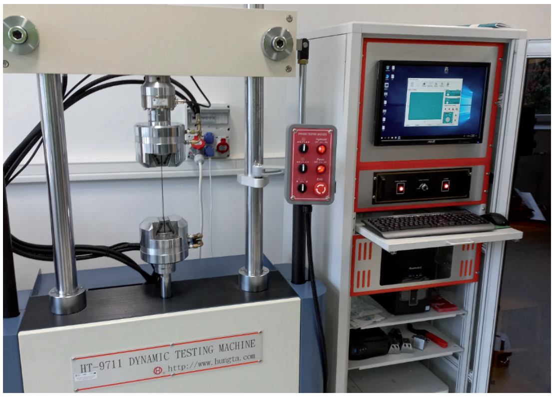

Figure 2: Arrangement of fatigue strength tests with attached specimen of adhesive joint.

The frequency f = 50 Hz and the stress ratio R = 0.1 were used. A sinusoidal load waveform was used. Four specimens were utilized at each level of fatigue load. The specimen set numbers are specified in Table 1 and Table 2. Then, the results of fatigue tests were subjected to statistical analysis and fatigue S–N curves were determined for both considered joint variants.

After the fatigue tests, selected specimens were subjected to fractography analysis. The fracture surfaces of the adhesive joints were analyzed with the use of a scanning electron microscope (SEM) Phenom ProX.

Static strength tests

The comparative tests of the static strength of the adhesive joints in the base variant 1 and the variant 2 with notches were done. The representative force-displacement curves obtained during the implementation of static shear strength tests are presented in Figure 3.

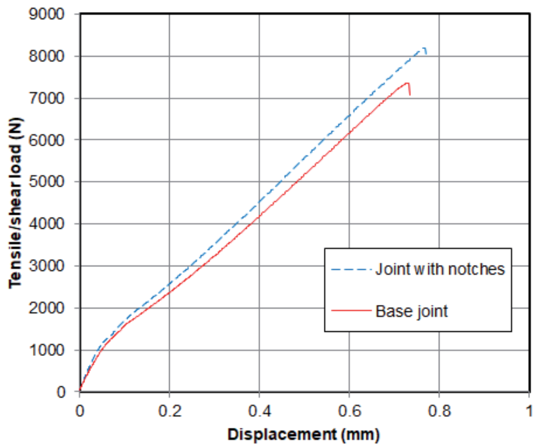

Figure 3: Representative shear load-displacement static test curves of adhesive joints of variant 2 with notches in relation to the base variant 1.

It can be observed from slopes of both curves in Figure 3 that the joints with notches are more rigid than the joints in the base variant 1. An increase in load capacity is also presented for notched joints. The average value of the load capacity for five specimens in the set V1S1 of the base variant 1 was 7446.94 N with standard deviation SD = 201.51 N. The average value of the load capacity for five specimens in the set V2S1 of notched variant 2 was 7612.44 N with standard deviation SD = 588.29 N.

The increase in load capacity was proved and the load difference is 2.2 %. The standard deviation of V2S1 specimen set is higher with the difference 191.9%. This higher standard deviation can indicate a lower repeatability. A higher scatter of strength test results may be caused by uneven filling of the notches with adhesive. The adhesive filling of notch spaces may contain random defects in its volume. For example, air bubbles may also contribute to the dispersion of results.

Fatigue tests

The static strength tests were intended for preliminary research of the impact of notches on the properties of the joints. The main aim of the manuscript is to determine the impact of the considered structural modifications on the fatigue properties of the joints. Tables 1 and 2 present the results of fatigue tests for individual tests, respectively for joint variant 2 with notches and for the base variant 1. The tables also include a statistical analysis of the fatigue test results.

Table 1: Results of fatigue tests and statistical analysis for joint variant 2 with notches.

Value of stress amplitude (MPa)	***Values for individual specimens***				
	15.5	**11.5**	**10.0**	**9.0**	**8.5**
Specimen set number	V2S2	V2S3	V2S4	V2S5	V2S6
Number of destructive cycles $N \times 10^3$	13.065 8.947 10.871 16.647	60.994 94.508 81.356 69.412	719.234 471.380 841.037 512.464	1,563.078 1,864.566 1,032.817 1,697.846	2,000.000 2,000.000 2,000.000 2,000.000
Logarithm of number of cycles lg*N*	4.11610 3.95167 4.03626 4.22133	4.78528 4.97546 4.91038 4.84143	5.85687 5.67337 5.92481 5.70966	6.19398 6.27057 6.01402 6.22989	6.30103 6.30103 6.30103 6.30103
Average value $\overline{N}$	12,382.5	76,567.5	636,028.75	1,539,576.75	2,000,000.0
Average value $\overline{\lg N}$	4.08134	4.87814	5.79117	6.17712	6.30103
Standard deviation s (SD)	0.09956	0.07155	0.10331	0.09798	-
Coefficient of variation $W_s = \frac{s}{\overline{\lg N}} \cdot 100\%$	2.439%	1.467%	1.784%	1.586%	-
Value t_α for confidence level p = 95% (α = 0.05)	3.182	3.182	3.182	3.182	-
$t_\alpha \cdot s$	0.31681	0.22769	0.32875	0.31179	-
log N_{up}	4.39815	5.10584	6.11993	6.48891	-
$N_{up} \times 10^3$ cycles	25.013	127.597	1318.056	3082.549	-
log N_{low}	3.76453	4.65044	5.4624	5.86532	-
$N_{low} \times 10^3$ cycles	5.814	44.714	290.018	733.381	-
Fatigue strength Z_G (MPa)	8.5				
Equation of linear regression of fatigue curve	σ = -3.000 E-06 x + 13.123				

Table 2: Results of fatigue tests and statistical analysis for base joint variant 1.

Value of stress amplitude (MPa)	***Values for individual specimens***				
	11.5	**10.0**	**9.0**	**8.5**	**8.0**
Specimen set number	V1S2	V1S3	V1S4	V1S5	V1S6
Number of destructive cycles $N \times 10^3$	19.832 10.684 8.312 13.845	75.865 38.691 65.894 56.623	258.133 469.874 298.416 615.642	941.642 1,646.310 1,346.584 1,005.479	2,000.000 2,000.000 2,000.000 2,000.000
Logarithm of number of cycles lg*N*	4.29736 4.02873 3.91970 4.14129	4.88004 4.58760 4.81884 4.75299	5.41184 5.67198 5.47482 5.78932	5.97388 6.21651 6.12923 6.00237	6.30103 6.30103 6.30103 6.30103
Average value $\overline{N}$	13,168.25	59,268.25	410,516.25	1,235,003.75	2,000,000.00
Average value $\overline{\lg N}$	4.09677	4.75987	5.58699	6.08050	6.30103
Standard deviation s (SD)	0.13982	0.10913	0.15118	0.09790	-
Coefficient of variation $W_s = \frac{s}{\overline{\lg N}} \cdot 100\%$	3.413%	2.292%	2.705%	1.610%	-
Value t_α for confidence level p = 95% (α = 0.05)	3.182	3.182	3.182	3.182	-
$t_\alpha \cdot s$	0.44491	0.34726	0.48105	0.31154	-
log N_{up}	4.54169	5.10713	6.06805	6.39204	-
$N_{up} \times 10^3$ cycles	34.809	127.977	1,169.634	2,466.304	-
log N_{low}	3.65185	4.41261	5.10593	5.76895	-
$N_{low} \times 10^3$ cycles	4.485	25.858	127.625	587.428	-
Fatigue strength Z_G (MPa)	8.0				
Equation of linear regression of fatigue curve	σ = -1.000 E-06 x + 10.417				

The impact of the applied notches on the fatigue properties of adhesive joints is analyzed from the comparison of fatigue curves of both variants with and without notches. The results from Table 1 and Table 2 are presented in Figure 4. The notches in adherends filled by adhesive have the significant impact on the fatigue characteristics of the joint in terms of low cycle fatigue. For a cyclic load with the stress amplitude of 11.5 MPa, the joints of specimen set V1S2 failed in average at 13,168.25 cycles. In comparison to these results, the fatigue lifetime of specimen set V2S3 with notches was increased to an average of 76,567.5 cycles, which is a significant increase of 481.5%. The joint specimen set V2S2 with notches in the adherends failed in average at 12,382.5 cycles. The applied load value of 15.5 MPa is a significantly higher load than the maximal load level of 11.5 MPa considered for the base variant 1.

Although, the differences of high cycle fatigue results of both specimen variants are lower than in low cycle fatigue, the impact of notches at adherends is also significant. The fatigue lifetime at the level of cyclic load equal to 9.0 MPa for the specimen set V1S4 was achieved at the average value of 410,516.25 cycles, while for the set V2S5 with notches it was on average 1,539,576.75 cycles. This represents an increase of 275%. With the assumed limit number of cycles equal to 2×10^6 cycles, the fatigue strength for the variant 2 was 8.5 MPa, while for the base variant 1 it was 8.0 MPa. Low cycle fatigue has a different fracture mechanism than high cycle fatigue. In the case of low-cycle fatigue, significant deformations occur in the joint area with each cycle. It can be assumed that the notches filled with adhesive absorb some of the deformation energy and therefore the increase in fatigue lifetime can occur.

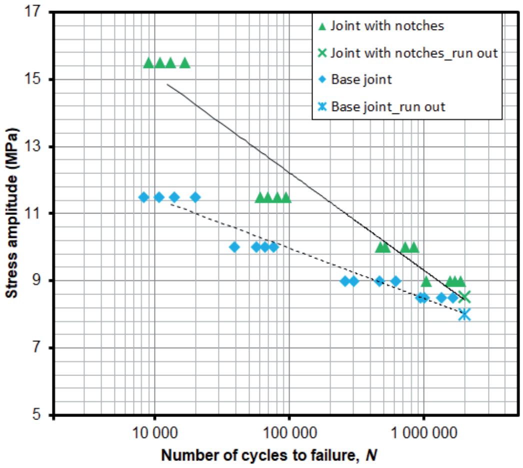

Figure 4: Fatigue diagram for considered adhesive joints subjected to high-cycle fatigue strength with a limited number of cycles equal to 2×10⁶.

Fractography analyses

In order to better recognize the impact of the notches made on the edges of the adherends on improving the fatigue lifetime, fractography analyses were performed for both variants of the considered adhesive joints. Figure 5 shows a macroscopic view and SEM images of selected areas of the fatigue fracture surface of the specimen number V1-S2-2. This specimen of the base joint variant 1, which failed after 10,684 cycles under a cyclic load with a maximum value of 11.5 MPa. Based on the view of the fatigue fracture on a macroscopic scale, three characteristic zones of fracture can be observed. At the leading edges of the joint, adhesive failure occurred in the majority of cases, with the adhesive remaining at the edge of the sheet on both adherends. The middle area of the fracture surface is a cohesive failure, while the fracture area from the side of the acting load is an adhesive failure, with the adhesive removed from this area because it remained on the surface of the second adherend. The following detail analysis of fractures in a microscopic scale, on the basis of SEM images, starts from the edge of the adherend sheet in the area of adhesive fracture. The damaged layer of brittle adhesive can be observed, which is a typical failure of thermosetting plastics. The nature of the fracture in this area may indicate that the typical adhesive damage did not occur here. This information was originally stated on the basis of macroscopic analyses. The brittle nature of the fracture indicates that the adhesive remained partially on the second adhesive element. This is confirmed by the SEM images taken from the direction of the applied load. The exposed metal surface and also the residues of the adhesive in Figure 5 proves the adhesive and cohesive damage. The only cohesive failure is presented in the middle area of the adhesive joint, where the SEM micrograph confirms the brittle fracture in the adhesive layer.

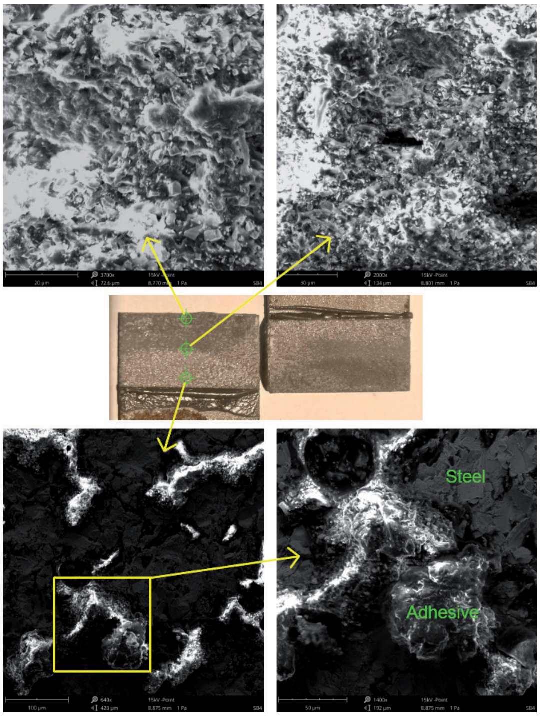

Figure 5: Fatigue fracture surface on a macroscopic scale and SEM micrographs of selected areas for the specimen V1-S2-2 of base joint variant 1, which was loaded with a fatigue stress of 11.5 MPa and failed after 10,684 cycles.

The following detail analysis of the fatigue fracture surface of the joint variant 2 with notches was done at the selected specimen V2S2-x, which failed after 10,871 cycles under the fatigue load with the amplitude value 15.5 MPa. Figure 6 shows a macroscopic view of the fatigue fracture of both adherends and SEM micrographs of selected areas. From the macro view, it can be seen that the fracture is uniform in this case compared to the base joint variant 1. Cohesive failure occurred over the entire surface of the fracture, which is desirable for adhesive joints. Only small areas locally show the nature of adhesive and cohesive failure. SEM micrographs focus on the notches of their edges. A different nature of damage can be observed in the area of the notch filled with adhesive and the surface of the sheet. In the area of the notch, the adhesive filling the space is an area of higher elasticity, because with each fatigue cycle, the entire volume of the adhesive in the notch is deformed in this area, so it is the volume of the adhesive with a thickness comparable to the thickness of the joined sheets equal to 2mm. On the other hand, in the main joint, the thickness of the adhesive layer is only about 0.1 mm. Differences in the nature of the deformation of the adhesive filling the notches and the adhesive layer between the sheets can also be observed on the basis of adhesive cracks appearing at the edges of the notches, which are visible in the SEM images. These cracks prove that the cyclic deformations of the adhesive filling the notches absorb a certain amount of energy, thus they can affect the inhibition of fatigue cracks occurring in the proper layer of adhesive between the sheets. The SEM micrographs also reveal that there is a significant amount of air bubbles in the indentation-filling adhesive.

The fractography analyses of fatigue fractures of specimens that failed in the area of high cycle fatigue are showed in Figure 7. The fatigue fracture surface of the specimen V1S4-4 of base joint variant 1 that failed after 615,642 load cycles with the maximum value of 9.0 MPa is presented in Figure 7, part a). Fatigue crack failures initiated at the edge of the sheet can be observed here. In this case, they overlap evenly, parallel to the edge of the sheet. After the crack reaches a certain critical size, the effective area of the joint decreases, and thus its weakening, which results in temporary cracking of the weakened cross-section.

The high-cycle fatigue fracture of the joint specimen V2S4-1 was analyzed in detail. This specimen failed after 719,234 load cycles with a maximum load value of 10.0 MPa. Figures 7, part b) and c) show the fracture area between the notches and characteristic adhesive fatigue failures can be seen here. The intensity of these failures on the sheet is significantly higher than in the area of notches, which is distinctly visible in Figure 7 part c). This confirms the earlier thesis that the adhesive filling

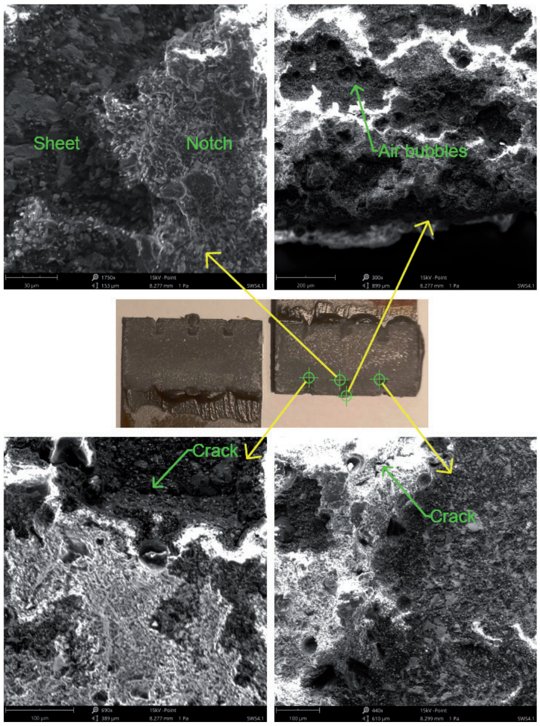

Figure 6: Fatigue fracture surface on a macroscopic scale and SEM micrographs of selected areas for the joint variant 2 with notches, which was loaded with a fatigue stress of 15.5 MPa and fractured after 10,871 cycles.

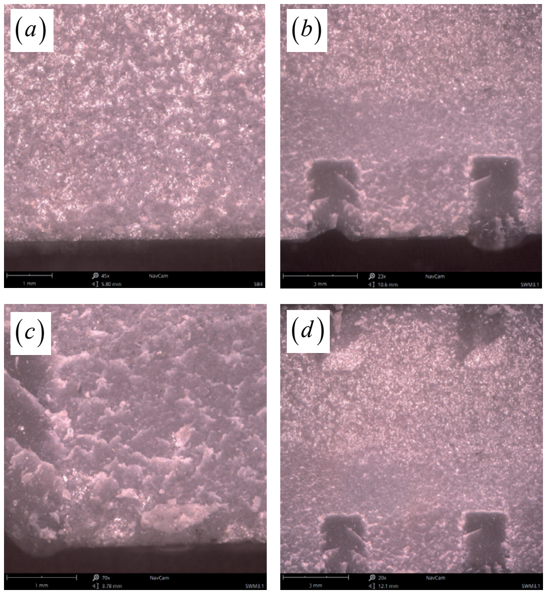

Figure 7: Fractography of fatigue fractures of adhesive joints that were subjected to high-cycle fatigue.
Figure 7 part a) is fracture surface of specimen V1S4-4 of base variant 1; Figure 7 part b), c) and d) are fracture surfaces of specimen V2S4-1 with notches.

the notches, due to its significantly higher thickness than the adhesive layer constituting the main joint, is characterized by higher elasticity, due to which fatigue cracking locally in these areas progresses more slowly. Due to the fact that a certain part of the deformation energy with each cycle is absorbed by the elastic deformation of the volume of the adhesive filling the notches, the intensity of fatigue cracking in the main adhesive layer is inhibited.

Based on the view of the fatigue fracture shown in Figure 7, part d), it was noticed that in the area of notches, various types of damage may occur. In the considered case, proceeding from the edge of the sheet, cohesive failure occurred in the frontal part of the notches, and adhesive failure occurred in the final part of the notches. This different type of failure may indicate that fatigue cracking progressed from the edge of the sheet to the area where cohesive failure was observed, while the area of adhesive failure may indicate temporary cracking of the weakened cross-section of the adhesive joint.

3. Conclusions

Based on the presented experimental studies, it was shown that the introduction of simple structural changes in adherends can contribute to a significant increase in fatigue lifetime. The most important conclusions from the conducted research are outlined below:

1. Static strength tests of the single lap shear joints showed that it is possible to increase the load capacity of the joint due to the use of notches in the adherends filled by adhesive. The average value of the load capacity for five specimens was 7446.94 N for joints in the base variant 1 and 7612.44 N for variant 2 with notches in adherends.

2. The average static load capacity and also the standard deviation of the joint variant 2 were increased

This may be caused by uneven filling of the notches with adhesive and impurities in the adhesive volume, such as air bubbles.

3. In the area of low-cycle fatigue, a significant increase in fatigue lifetime was proved due to the use of notches in adherends. For a cyclic load with a maximum value of 11.5 MPa, the joints in the base variant 1 failed on average after 13,168.25 cycles. In comparison, the fatigue life of joints with notches increased to an average value of 76,567.5 cycles, which is a significant increase of 481.5%.

4. The increase in fatigue lifetime caused by the introduction of notches in adherends, which are filled with adhesive, may be due to the fact that the adhesive filling the notches with a significantly higher thickness than the adhesive forming the main joint layer absorbs part of the deformation energy due to higher susceptibility to plastic deformation.

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