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EXPERIMENTAL STUDY OF THE IMPACT OF CHAMFER AND FILLET IN THE FRONTAL EDGE OF ADHERENDS ON THE FATIGUE PROPERTIES OF ADHESIVE JOINTS SUBJECTED TO PEEL

BADANIA EKSPERYMENTALNE WPŁYWU FAZY I PROMIENIA NA CZOŁOWEJ KRAWĘDZI ELEMENTU KLEJONEGO NA WŁAŚCIWOŚCI ZMĘCZENIOWE POŁĄCZEŃ KLEJOWYCH PODDANYCH ODDZIERANIU

Abstract

The paper presents the influence of simple structural modifications of the adherend on the fatigue properties of adhesive joints subjected to peel. The considered modifications consisted in making a chamfer and fillet on the front edge of the adherend. The purpose of such modifications was to locally increase the thickness of the adhesive layer in the area of stress concentration. Fatigue strength tests were carried out using an electrodynamic shaker at the resonant frequency of the flexible adherend.

On the basis of fatigue strength tests carried out at the limited number of cycles equal to 2×10^6, it was shown that a local increase in the thickness of the adhesive layer in the front part of the joint allows a significant increase in the joint's fatigue lifetime and fatigue strength. The greatest effect was shown for the variant with the fillet R2. In this case, an increase in fatigue strength of 33.1% compared to the base variant was demonstrated. For the fatigue stress level of 20.25 MPa, an increase in fatigue lifetime of 337.7% was also demonstrated. Based on the conducted research, it was shown that the reason for the improvement of the fatigue properties of the joints due to the local increase in the thickness of the adhesive layer is the phenomenon of energy absorption in the frontal area of the joint. Absorption of energy that inhibits the process of fatigue results from, among others, local flexibility of the joint, as well as nucleation of cracks in the locally increased volume of the adhesive.

Keywords: adhesion, adhesive joints, fatigue strength, high cycle fatigue, S–N curves

Streszczenie

W pracy przedstawiono wyniki badań określających wpływ modyfikacji konstrukcyjnych elementu klejonego na właściwości zmęczeniowe połączeń klejowych poddanych oddzieraniu. Rozważane modyfikacje polegały na wykonaniu fazy oraz promienia na czołowej krawędzi elementu klejonego. Celem takich modyfikacji było miejscowe zwiększenie grubości warstwy kleju w obszarze koncentracji naprężeń. Badania wytrzymałości zmęczeniowej przeprowadzono za pomocą wzbudnika elektrodynamicznego przy częstotliwości rezonansowej klejonej płytki. Na podstawie badań wytrzymałości zmęczeniowej przeprowadzonych przy granicznej liczbie cykli równej 2×10^6 wykazano, że lokalny wzrost grubości warstwy kleju w czołowej części złącza pozwala na znaczny wzrost trwałości zmęczeniowej oraz wytrzymałości zmęczeniowej. Najkorzystniejszy efekt wykazano dla wariantu z promieniem R2. W tym przypadku wykazano wzrost wytrzymałości zmęczeniowej o 33,1% w stosunku do wariantu bazowego. Dla poziomu naprężenia zmęczeniowego 20,25 MPa wykazano również wzrost trwałości zmęczeniowej o 337,7%. Na podstawie przeprowadzonych badań wykazano, że przyczyną poprawy właściwości zmęczeniowych połączeń na skutek lokalnego zwiększenia grubości warstwy kleju jest zjawisko pochłaniania energii w obszarze czołowym złącza. Absorpcja energii hamująca proces zmęczenia wynika m.in. z miejscowego uelastycznienia złącza, jak również zarodkowania pęknięć w lokalnie zwiększonej objętości kleju.

Słowa kluczowe: adhezja, połączenia klejowe, wytrzymałość zmęczeniowa, wysokocyklowe zmęczenie, krzywe S–N

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1. Introduction

Nowadays, adhesive joints are widely used especially in those areas of industry where it is desirable to reduce the weight of a product. One of the most important advantages of the structural adhesive joining technique is the ability to join different materials and the uniform distribution of stress in the area of a joint. These are the main reasons why adhesive joining is used in the technology of composite materials commonly used in the aircraft industry. They demonstrate high temperature resistance and high adhesiveness performance [1-3]. Apart from a number of unquestionable advantages, there are also significant drawbacks of adhesive joined structures, such as relatively low durability and fatigue strength, when compared to other joining techniques [4-7]. The best polymer materials for adhesive bonding, with high cohesive performance, are epoxy resin adhesives [8].

The strength properties of adhesive-bonded joints depend on many factors. The most important ones are the type of the applied adhesive composition [9], the methodology of preparing surfaces of adherends before joining, the adhesive hardening conditions of the bonding process, and the thickness of the adhesive layer [10-11].

Many references state that the optimal thickness of an adhesive layer is about 0.05-0.15 mm [12]. However, in the case of a loaded joint, there is a phenomenon of stress concentration occurring near the frontal edge of a joint.

The authors of [13] performed the FEM analysis of a single lap joint with the geometrical modification of adherends. They considered different sizes of the chamfer on the frontal part of an adherend and proved by FEM that it is possible to significantly reduce stress concentration.

Other references [14] reported that the geometrical modifications of an adherend could improve the shear strength of a single lap of an adhesive joint by 20%.

In the article [15], the authors described the FEM analysis of a single lap of adhesive joints subjected to the shear with the fillet on adherends. It also proves that there is a possibility to improve the strength of adhesive joints by the fragmentary enlargement of an adhesive layer.

Because of the increase in the application of structural bonded technology, it is desirable to develop every method to improve adhesive joining, which is the purpose of the presented research.

The presented results are the continuation of the research related to the static strength tests [16] and the FEM analysis of adhesive joints with geometrical modifications of an adherend.

In this work, experimental studies were carried out to analyze the effect of structural modifications on the front edge of the adherends on the fatigue strength properties. Peel fatigue strength tests were carried out for adhesive joints of rigid and flexible adherends. The tests were carried out at the resonant frequency of the flexible adherend. The applied modifications consisted in making a chamfer and fillet in one of the adherend, which was aimed at locally increasing the thickness of the adhesive layer in the frontal area of the joint. A comparison of the fatigue curves for the variant with the modification in the form of chamfer and fillet and the base joint was made. Fractographic analyses were carried out for selected joints using SEM microscopy.

2. Materials and methods

The research was conducted for the specimens that consist of adherends made with S235JR steel (EN 10025/2-2004). The shape and dimensions of the specimens are shown in Fig. 1. The research on the fatigue strength and the fatigue lifetime of the adhesive joints subjected to peel were carried out for particular variants. The fatigue tests were high-cyclic for a limited number of cycles 2×10^6.

The uniform methodology of preparing surfaces of adherends was used. The surfaces were sand-blasted with aloxite 95A and cleaned with acetone. The parameters of the sand-blasting operation were as follows: the size of grain a = 0.27 mm, the pressure of compressed air p_s = 0.8±0.1 MPa, and the time of exposure t_s = 60s.

Surface morphology analysis of the adherends was performed according to ISO 25178 standard using AltiMap Gold software based on the non-contact optical measurement system of Talysurf CCI Lite 3D (Taylor Hobson, England).

The example of surface morphology of flexible adherend after the sandblasting process is shown in Fig. 2. The main standard 3D parameters determined by this measurement (Table 1) are the root mean square roughness parameter Sq, the average roughness Sa, surface kurtosis Sku, surface skewness Ssk, the 10-point peak-valley surface roughness Sz, the highest peak of the surface Sp, and the maximum pit depth Sv.

Chemically hardening epoxy adhesive was used in the tests – Bison Epoxy PLUS ENDFEST (supplied by Bison International B.V., Rotterdam, Netherlands).

The hardening process took place under the following conditions: room temperature (20±3°C), the time of hardening t = 24 h, load on the area of a joint p = 0.01 MPa.

The rigid adherends were modified by making the chamfer or fillet to locally enlarge the thickness of an adhesive layer with the aim to reduce the peel stress concentration in the frontal part of a joint. The dimensions of the applied structural modifications at the front edge of the rigid adherend are shown in Fig. 3. Comparative fatigue tests were carried out for the base variant, thus without structural modifications, and variants with chamfer 2×2 (Fig. 3a), chamfer 2×4 (Fig. 3b) and fillet R2 (Fig. 3c). For each variant, 16 samples of adhesive joints were prepared.

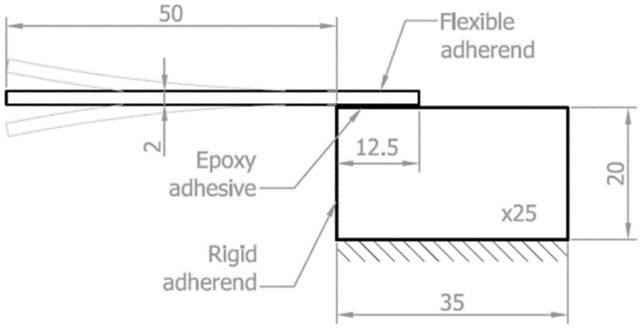

Figure 1. Shape and dimensions (in mm) of adhesive joint samples used in fatigue tests

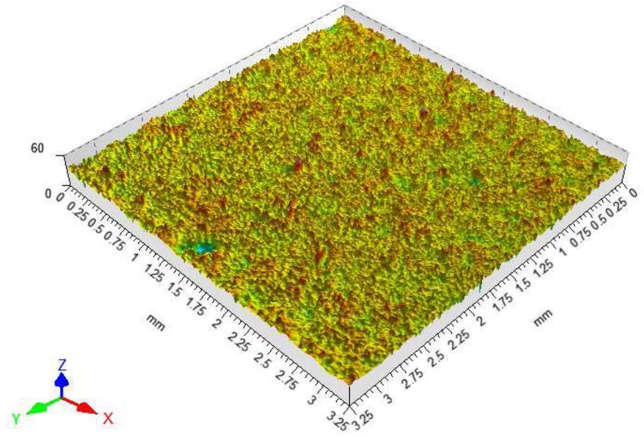

Figure 2. An example of surface morphology of the flexible adherend after sand blasting process

Table 1. Values of the basic surface roughness parameters of the flexible adherend subjected to the sandblasting process

Parameter	Sq	Ssk	Sku	Sp	Sv	Sz	Sa
Value	3.92 µm	-0.447	4.98	24.6 µm	35.4 µm	60.0 µm	2.98 µm

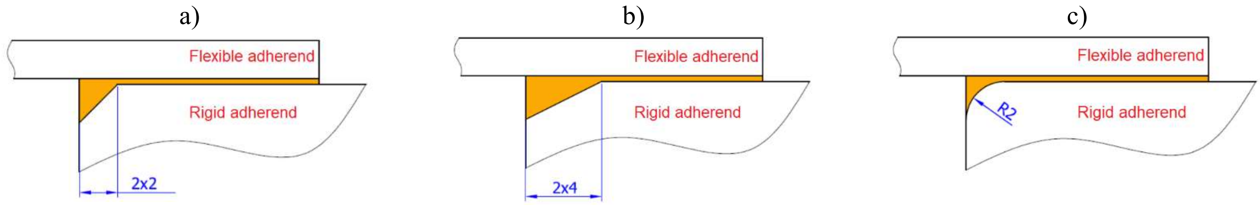

Figure 3. Dimensions (in mm) of applied structural modifications of the rigid adherend, variant chamfer 2×2 (a), chamfer 2×4 (b), and fillet R2 (c)

The research on the fatigue strength and the fatigue lifetime was carried out with the electrodynamic conductor ETS SOLUTION L Series MPA-102-L620M.

The fatigue tests were carried out at the resonance frequency of flexible adherend. The value of the resonance frequency was automatically searched by special software. The fatigue test system was equipped with the accelerometer and laser system to measure the amplitude of the vibration of the flexible adherend.

The value of the resonant frequency of the samples was in the range of 540-580 Hz. During the fatigue test, due to the process of fatigue cracking of the adhesive layer, the resonance frequency gradually decreased. Immediately before the complete destruction of the joint, it reached a value in the range of 360-390 Hz.

For a given value of the vibration amplitude of the flexible adherend tip, the value of normal stresses in the adhesive layer was determined using the FEM. The three-dimensional FEM model was made using the ABAQUS 6.10-2 software. Table 2 presents the vibration amplitude values considered in the tests with the corresponding maximum values of normal stresses determined using the FEM analysis for individual variants.

Table 2. Vibration amplitude values with the corresponding maximum values of peel stresses (according to FEM analysis) for the considered variants

Base variant				
Maximal adhesive peel stress (MPa)	20.25	17.55	14.85	13.98
Amplitude (mm)	0.75	0.65	0.55	0.5
Variant chamfer 2×4				
Maximal adhesive peel stress (MPa)	19.27	17.34	15.41	13.40
Amplitude (mm)	1	0.9	0.8	0.7
Variant chamfer 2×2				
Maximal adhesive peel stress (MPa)	20.94	19.27	16.24	14.12
Amplitude (mm)	1	0.9	0.8	0.7
Variant fillet R2				
Maximal adhesive peel stress (MPa)	22.65	19.94	18.27	16.24
Amplitude (mm)	1.1	1	0.9	0.8

All variants of specimens were tested on four levels of dynamic loading. On every level, the tests were repeated four times. The lowest level of the dynamic load was the value at which the specimen did not fail after being loaded by 2×10^6 cycles. Fig. 4 shows the view of the fatigue test stand with a sample of the adhesive joint.

The morphologies of the fracture surfaces of the adhesive joints were examined using an scanning electron microscope (SEM) Phenom ProX (Nanoscience Instruments, Phoenix, AZ, USA).

Figure 4. Setup for fatigue testing of adhesive joints

3. Results and discussion

Figs. 5-7 show the fatigue curves for the considered variants of joints in relation to the fatigue curve for the base variant. The most favorable results related to the local increase in the thickness of the adhesive layer were shown for the case in which fillet R2 was made (Fig. 5). For this variant, the fatigue strength increased by 33.1% compared to the base variant, for which the fatigue strength was Z_G = 12.2 MPa (Fig. 5). For the fillet R2 variant, the greatest increase in fatigue life was also shown. Considering the fatigue life for the fatigue stress level of 20.25 MPa, the average fatigue life for the base variant was 128×10^3 cycles, while for the fillet R2 variant, the fatigue lifetime was 562×10^3 cycles on average. Thus, a significant increase in fatigue lifetime by 337.7% was demonstrated.

For the remaining variants with a locally increased thickness of the adhesive layer, a significant improvement in durability and fatigue strength was also demonstrated. In the case of the chamfer 2×2 variant, the fatigue strength increased by more than 15% compared to the base variant (Fig. 6). Moving on to the chamfer 2×4 variant, it should be noted that in the area of low cycle fatigue, i.e. below 10^5 fatigue cycles, no significant differences were found compared to the base variant. However, in the area of high cycle fatigue, significant differences have already been shown, and the fatigue strength has increased to Z_G = 14.4 MPa (Fig. 7), which is an increase of over 18% in relation to the base variant.

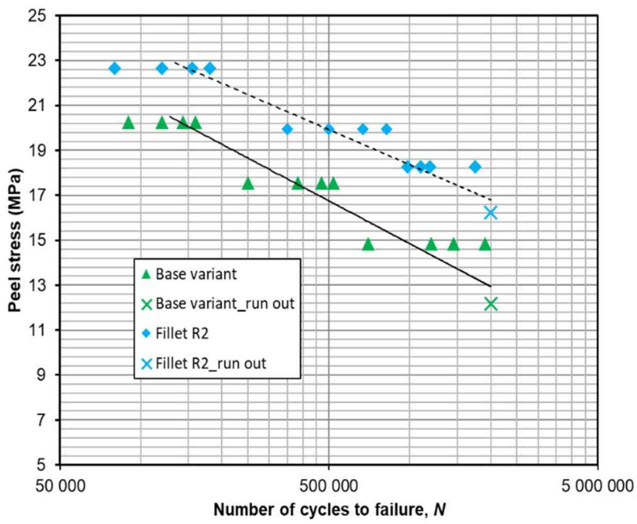

Figure 5. Comparison of the fatigue curves for the base variant and fillet R2 variant

Since the best results were shown for the fillet R2 variant, it can be concluded that this variant is the most favorable because it is devoid of edges. This is an important issue because stress concentration occurs in the frontal area of the joint, each sharp edge acts as a notch in this critical area.

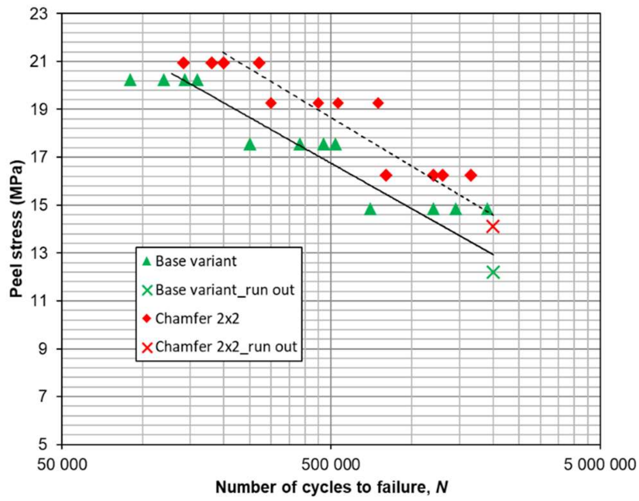

Figure 6. Comparison of the fatigue curves for the base variant and chamfer 2×2 variant

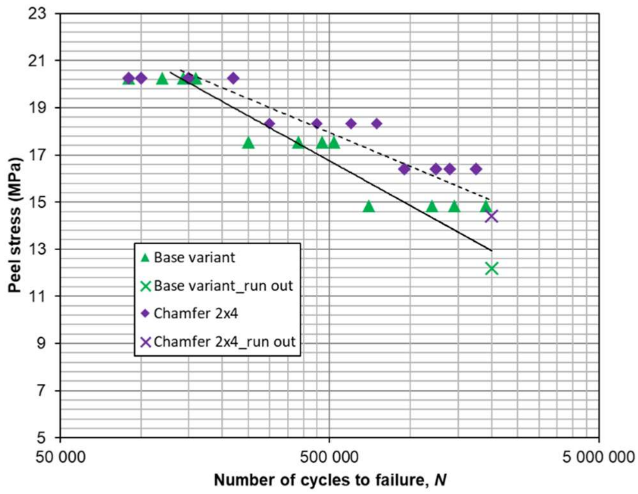

Figure 7. Comparison of the fatigue curves for the base variant and chamfer 2×4 variant

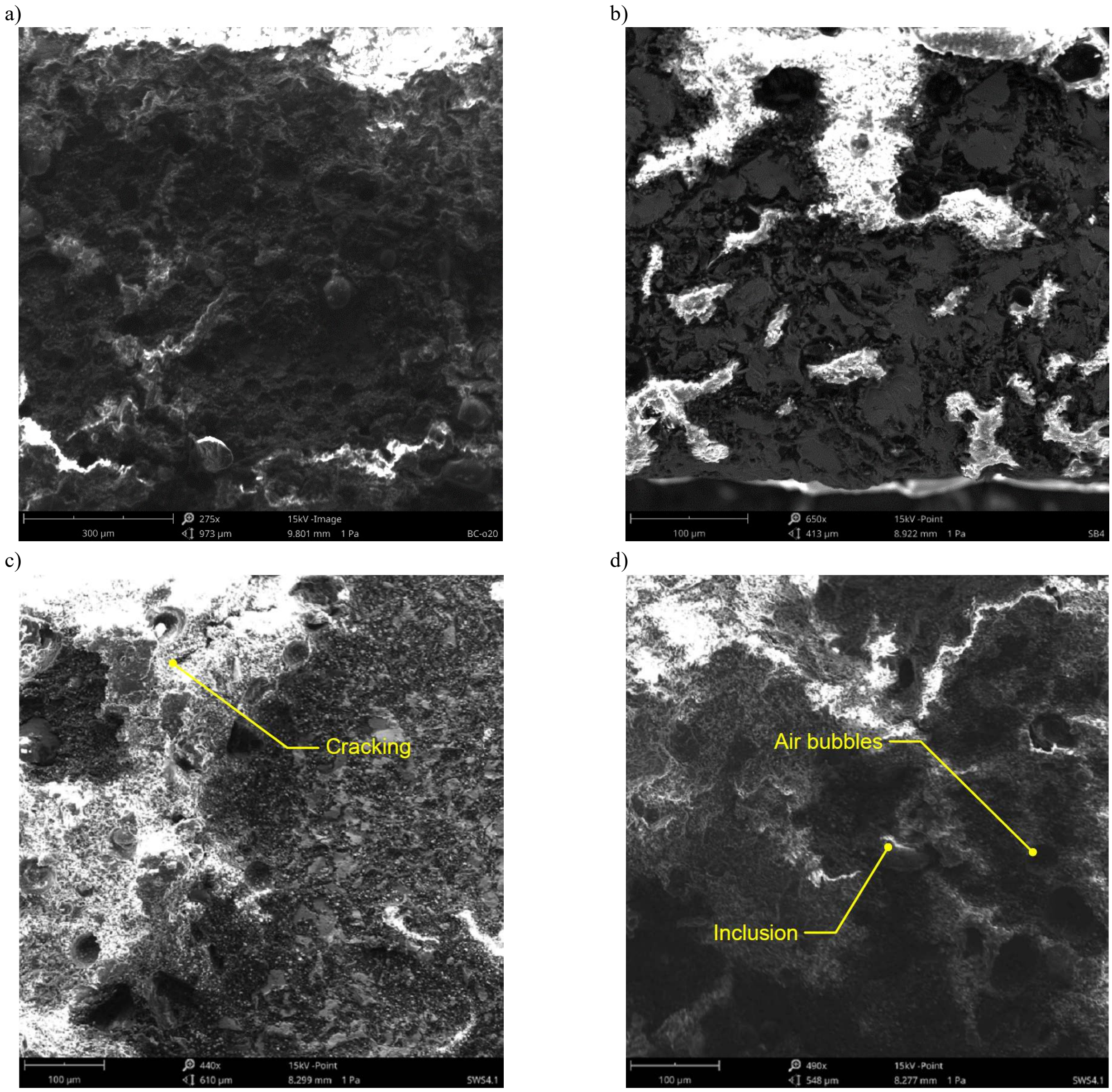

Figure 8. SEM micrographs of fatigue fractures of the front joint area for the following variants: base (a, b), fillet R2 (c), chamfer 2×2 (d)

e)

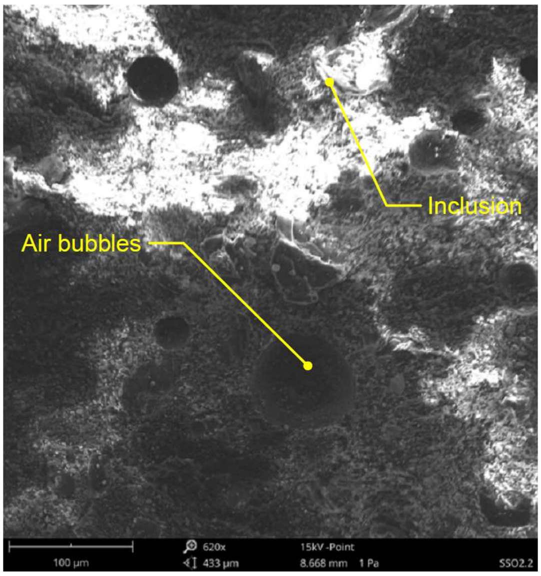

Figure 8 (cont.). SEM micrographs of fatigue fractures of the front joint area for the following variants: chamfer 2×4 (e)

When analyzing the fatigue fractures, it can be observed that for the joints in the base variant, there was generally a uniform form of joint failure in the area of its entire surface. Adhesive failure dominates here (Fig. 8a), although areas of mixed adhesive/cohesive failure also occur sporadically (Fig. 8b). Moving on to variants with structural modifications in the area of a local increase in the thickness of the adhesive layer, the space-filling adhesive is an area of greater elasticity. Therefore, with each fatigue cycle, the entire volume of the adhesive located in the frontal region is deformed in this region. At the joint face, the thickness of the adhesive layer is 2 mm, while 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 front part and the adhesive layer between the sheets can also be observed on the basis of adhesive cracks appearing in areas with increased adhesive layer thickness, which are visible in the SEM micrograph for the fillet R2 variant (Fig. 8c). These cracks prove that the cyclical deformations of the adhesive layer of increased thickness absorb a certain amount of energy, thus they may influence the inhibition of fatigue cracks occurring in the proper adhesive layer between the sheets. However, it should be borne in mind that filling the space with adhesive requires great technological care, as it has been shown that in the areas filling the chamfer and fillet, there may be a high intensity of air bubbles, as well as inclusions, which is shown in the SEM micrographs for the chamfer 2×2 variants (Fig. 8d) and chamfer 2×4 (Fig. 8e).

4. 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. The possibility of a significant improvement in fatigue strength was demonstrated by using a structural modification consisting of a local increase in the adhesive layer in the frontal area of the joint. For the fillet R2 variant, an increase in fatigue strength by 33.1% was shown in relation to the base variant.
2. For the fillet R2 variant, the possibility of a significant increase in fatigue life was demonstrated, with a variable load of 20.25 MPa, and an increase in fatigue lifetime by 337.7% was demonstrated.
3. The hypothetical reason for the improvement in the strength and fatigue life of the joints with the applied structural changes is the local increase in the thickness of the adhesive layer. In the area of a local increase in the thickness of the adhesive layer, the space-filling adhesive is an area of greater elasticity. Cyclic deformations of the adhesive layer of increased thickness absorb a certain amount of energy, thus they can influence the inhibition of fatigue cracks occurring in the proper adhesive layer between the sheets.
4. In the leading areas with an increased thickness of the adhesive layer, cracks in the adhesive

volume were observed as a result of fatigue. This proves that the locally increased adhesive layer at the joint front absorbs a certain amount of energy, thus inhibiting fatigue in the main joint.
5. The most favorable effect related to the improvement of durability and fatigue strength was shown for the fillet R2 variant, which is due to the lack of notches in the form of edges in the front part of the joint, where stress concentration occurs.

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