Fatigue life thick-bonded glued joints subjected to aging

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Abstract. The paper presents the results of experimental tests under static and cyclic loads of thick-layer adhesive joints. The test specimens were made of X2CrNi12 steel sheet (PN-EN 10027-1: 2007), 1.6 mm thick. BETAMATE BTR adhesive was used for gluing. Bonding was carried out under strictly controlled conditions, i.e. 20 °C and 23 % humidity. The specimens underwent aging in various conditions. Subsequently, experimental tests were carried out under static load. The obtained results allowed to determine: tension strength of glued joints $S_u$, yield stress $S_{y0.2}$, elastic modulus $E$ and elongation $\Delta L$. Plots of static strength allowed to calculate the value of work $W$, needed to damage the joint. The second stage of the research covered of determination of the aging effect of the specimens on fatigue life. The research was carried out in the conditions of constant amplitude loads with asymmetric cycle coefficient $R = 0$. The obtained results allowed to assess the influence of the aging process of adhesive joints on its fatigue life.

1. Introduction
The use of glued joints in machine building is commonly used, which is confirmed by examples of aircraft, trains, buses, etc. The advantages of this type of connections include [1-5]:

- The possibility of combining materials with different physical properties.
- Joining construction elements without creating additional geometric notches.
- The possibility of obtaining tight connections.
- High durability achieved thanks to the use of modern structural adhesives.
- The ability to correct the shape errors of the joined elements.
- Corrosion resistance.
- The ability to damp vibrations.

The stapled joint stuck during tensile is damaged by shearing and tearing. A disadvantageous tearing joint is caused by the deformation of the stretched connecting elements (Figure 1). The strain appear as result asymmetric, one-sided transfer of load from one element to another, which leads to the bending of the sample. In the case of joining elements with the same stiffness, the stress distribution in the connection is shown in Figure 1. Is visible symmetrical increase of stresses at the ends of the joint [6], [7].

The combination of elements with different stiffness causes that stress distribution is not symmetrical, and the maximum occurs at the edge of the stiffer part. Stiffness imbalance is the ratio of the rigidity of the stiffer element to the stiffness of the other connected part. With the increase in stiffness imbalance, the effectiveness of the connection decreases, expressed as the ratio of mean stresses to maximum stresses. Examples of test results for this type of connections are described in [2], [8].
Adhesive-bonded joints in operating conditions can be subject to loads about high variability $\sigma_m$ and $\sigma_a$ cycles. The range of variability $\sigma_m$ and $\sigma_a$ is determined by various factors and the operating conditions. The nature of operating loads significantly affects the fatigue life of machine components and is related with the number of cycles at high amplitude $\sigma_a$, stress range $\Delta\sigma$ and the course of the changes [3], [9]. Tests can be performed with a constant or gradually increasing amplitude [3], [10].

The aim of the work is to evaluate elastic thick-layer glued joints subjected to aging under static and cyclic loads. The conducted aging process of test objects was simulated the actual load conditions of this type of connection in rail vehicles. The materials used and the technology used to build test samples are commonly used in the construction of rail vehicles.

2. Material and method

The glued material was a sheet of 1.6 mm thickness made of X2CrNi12 steel (polish standard: PN-EN 10027-1: 2007). The shape of the specimen resulted from the guidelines of PN-EN 1465:2009 (polish standard). Strips of length 100 and width 25 mm were cut from the sheet. The strips were degreased (BETACLEAN 3350 degreaser), and then ground with fine-grained sand paper (granulation 180) at the area to which the joint will be applied. Next, they were degreased with the same product again. For gluing, the strips were placed in a special holder that ensures proper positioning of the plates relative to each other, and thus the required shape and dimensions of the joint (according guidelines of DVS 1618:2002). BETAMATE BTR glue was used for gluing. Gluing was performed in strictly controlled conditions, i.e. 20 °C temperature and 23 % humidity. After gluing the specimen were left to dry for 7 days in the same conditions. Figure 2 shows the shape of prepared specimen. After aging, the specimen were kept for 2 hours in ambient temperature (DIN 54457), after which the tests were performed [11].

The specimens were aged according to the guidelines specified in DIN 54457 and DIN EN ISO 9142. Specimen aging methods are specified in Table 1. The specimens were divided into four groups.

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**Figure 1.** Distribution of tangential stresses in a joint made of the same materials [7].

**Figure 2.** Shape and dimensions of the test specimen.
Table 1. Aging methods of specimens [11].

| Group | Aging method                                                                 |
|-------|-----------------------------------------------------------------------------|
| G1    | Samples not aged                                                            |
| G2    | Samples stored for 1 week in water in 20ºC temperature                      |
| G5    | Samples stored for 4 weeks in water in 20ºC temperature                      |
| G7    | Samples stored for 1 week in water in 20ºC temperature, then tightly closed (using foil not permitting air and humidity) in 70ºC temperature (so-called cataplasma test) |

Tests were performed with using Instron ElectroPuls E3000 testing device (Instron, High Wycombe, England). Washers of appropriate thickness were used when fixing the samples to the machine holders, to ensure action of the load along the joint. Tests were conducted in temperature 20 ºC.

3. Results

3.1. Static tensile test results

The assessment of properties of bonded joints under static load conditions was carried out under displacement control. The value of displacement was 0.005 mm/s. The exemplary test results for each group of samples are shown in Figure 3. On the basis of the determined static tensile stabilities \( \tau = f(\Delta L) \), the limit of proportionality \( S_{y,0.2} \), strength of the \( S_u \) connection, elastic modulus \( E \) and elongation \( \Delta L \) were determined. The average values of the parameters are shown in Table 2.

![Figure 3. Exemplary plots of static tensile strength: G1 group – a), G2 group – b), G5 group – c), G7 group – d).](image-url)
Table 2. Results static tensile test.

| Group | $S_{y_{0.2}}$ | $S_u$ | $E$ | $\Delta L$ |
|-------|--------------|--------|------|----------|
|       | MPa          | MPa    | MPa  | mm       |
| G1    | 3.8          | 4.6    | 503.9| 15.2     |
| G2    | 4.2          | 4.6    | 459.2| 14.6     |
| G5    | 3.7          | 4.4    | 661.5| 10.8     |
| G7    | 3.9          | 4.6    | 647.6| 11.9     |

The obtained results of static test shows the influence of the aging process on elongation of samples. The highest elongation was obtained for the G1 group (15.2 mm), and the lowest values for the G5 group (10.8 mm). It can be assumed that the extension of $\Delta L$ was connected with value of the elastic modulus $E$. The highest values $E$ were obtained for G5 group, the lowest value for G1. Values $S_u$ and $S_{y_{0.2}}$ were similar for all groups.

Based on graphs showed in Figure 3 was calculated the value of the work $W$, needed to destroy sample. Each of the characteristics $\tau = f(\Delta L)$ was subjected to integration, which allowed to calculate the area under the graph. The average value of work $W$ is shown in Figure 4.

![Figure 4](image_url)

**Figure 4.** The average value of work $W$ for investigated groups.

The highest value of work $W$ was obtained for the G1 group, the lowest for G5 group. It was result the shape of curve $\tau = f(\Delta L)$, maximum value of force and elongation $\Delta L$.

### 3.2. Cyclic test results

Fatigue tests were carried out under programmable stress. Constant amplitude load were used, cycle

![Graph a](image_url)

![Graph b](image_url)
asymmetry factor R = 0. The levels of stress amplitude \( \tau_a \) were chosen: \( \tau_a = 1.28; 1.92; 2.56 \) and \( 3.20 \) MPa. The frequency of test was 1 Hz.

The samples were subjected to a uniaxial constant-amplitude tensile load. Based on the experimental results, fatigue life \( \tau_a - N \) diagrams were determined. The plots and equations describing fatigue life are shown in Figure 5.

4. Analysis of results of cyclic test

Differences between fatigue life test results were analyzed on the basis of the difference of the relative life \( \delta_N \) calculated from the equation:

\[
\delta_N = \frac{N_{cG1}^{(i)} - N_{cG1}}{N_{cG1}} \cdot 100\%
\]

where: \( N_{cG1}^{(i)} \) – number of cycles till fatigue crack for \( \tau_a \) group \( G1 \) and \( N_{cG1} \) – number of cycles till fatigue crack for \( \tau_a \) groups \( G2, G5 \) and \( G7 \).

The results of calculations are presented in Figure 6. The relative difference in fatigue life \( \delta_N \) for the assumed aging processes is:

- group \( G2 \): \( \delta_N = -14.7 \div 0.3 \% \).
- group \( G5 \): \( \delta_N = -16.2\% \div 0.1\% \).
- group \( G7 \): \( \delta_N = -27.7\% \div -9.0\% \).

![Figure 5](image)

"Figure 5. Plots of fatigue life of glued joints for constant-amplitude load and cycle asymmetry factor R=0: group G1 – a), group G2 – b), group G5 – c), group G7 – d)."

![Figure 6](image)

"Figure 6. Relative differences in fatigue life samples subjected to aging."
5. Conclusions
Analysis of the static tensile test results shows that the aging process affects the change of the following parameters of the glued joints: elongation $\Delta L$, Young's modulus $E$ and work $W$.

The conducted analysis indicates that along with decreasing the stress value, the fatigue life of samples subjected to aging decreases. The largest decrease was observed for G7 group. In the case of G2 and G5 groups, similar fatigue life results were obtained, but smaller than obtained for G1 group.

Experimental tests of adhesive joints samples based on BETAMATE BTR adhesive under cyclic loading conditions indicate that the aging process affects the change of Young's modulus $E$, elongation $\Delta L$ and work $W$. The highest value of elongation and work was observed for samples of glued joints, which have not been subjected to aging.

Experimental tests of fatigue life of glued joints in the conditions of constant-amplitude load about $R = 0$ showed differences, the value of which depends on the stress amplitude $\tau_a$ and the kind of aging method.

References
[1] Adams R and Wake W 1984 Structural Adhesive Joints in Engineering, Elsevier
[2] Maćkowiak P and Ligaj B 2017 Damage to Adhesive Single Lap Joint Made of Materials with Different Properties Under Static Loading Conditions, 23rd International Conference on Engineering Mechanics EM, Svatka, Czech Republic, May 15-18, pp. 598-601
[3] Wirwicki M and Topolinski T 2013 Determining the S-N Fatigue Curve for Lava Zirconium Dioxide, Advanced Materials Research 845 153-157
[4] Kuczmaszewski J 1995 Construction and Technological Principles for the Assessment of the Strength of Adhesive Metal Connections (Podstawy konstrukcyjne i technologiczne oceny wytrzymałości adhezyjnych połączeń metali), Wydawnictwa Uczelniane
[5] da Silva L, Dillard D, Blackman B and Adams R 2012 Testing Adhesive Joints, John Wiley & Sons
[6] Godzimirski J 2002 Ad Hoc Strength of Structural Adhesive Joint (Wytrzymałość doraźna konstrukcyjnych połączeń klejowych), Wydawnictwo Naukowo-Techniczne
[7] Hart-Smith L J 1973 Contract Report, NASA CR-112235
[8] Godzimirski J, Komorek A and Smal T 2007 Tests of strength properties of adhesives (Badania właściwości wytrzymałościowych tworzyw adhezyjnych), Problemy eksploatacji 1 157-165
[9] Zastempowski M, Bochat A and Wesołowski L 2015 A Comparative Study of New and Traditional Designs of Hammer Mill, Transaction of the ASABE 58(3) 585-596
[10] Topolinski T, Cichanski A, Mazurkiewicz A and Nowicki K 2012 Applying a Stepwise Load for Calculation of the S-N Curve for Trabecular Bone Based on the Linear Hypothesis for Fatigue Damage Accumulation, Materials Science Forum 726 39-42
[11] Topolinski T, Ligaj B, Mazurkiewicz A and Miterka S 2017 Evaluation of Deformations of Thick-Layer Glued Joints Applied in Construction of Rail Vehicles, 23rd International Conference on Engineering Mechanics EM, Svatka, Czech Republic, May 15-18, pp. 986-989