Determination of opening force of hot-melt adhesive joints in flexible packaging

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Abstract

Introduction. Numerical modeling of the strength of hot-melt adhesive joints in flexible packaging materials allows for predicting the peel force values to achieve consumer-friendly packaging joint strength.

Materials and methods. For experimental tensile strength testing, three types of packaging materials were used: offset paper, cardboard, and polyethylene, which were subsequently bonded with a hot-melt adhesive. The hot-melt adhesive is based on EVA (ethylene-vinyl acetate). Numerical modeling was conducted to analyze the failure of the hot-melt adhesive joint, aiming to predict the initiation and propagation of failure under static loads.

Results and discussion. A mathematical model is proposed that allows experimentally determined resistance values to be used to calculate the maximum failure force. A numerical determination of the contact zone strength was performed, which enables the calculation of the failure force. The dependencies of the force at the edges of samples made from the three packaging materials on displacement for both experimental values and those obtained from numerical modeling were found. It was shown that plasticity zones arise on the interface surface when maximum stress is reached, leading to unloading in the local zone of the sample material. As the joint continues to fail, the breaking forces gradually decrease. The dependencies of forces at the edges of samples made from paper, cardboard, and polyethylene on the displacement of the sample edges during stretching were obtained. The appearance of the experimental curves of the dependence of the applied forces on the displacement corresponds to the model of nonlinear elastic-plastic failure of the adhesive zone. It was found that under the considered bonding conditions, the total peel force for paper materials is 0.1 N/mm, for cardboard materials – 0.22 N/mm, and for polyethylene materials – 0.75 N/mm. The highest force value among the bonded samples was observed for polyethylene. This can be explained by the fact that, during bonding with hot-melt adhesive, some films undergo welding rather than just bonding.

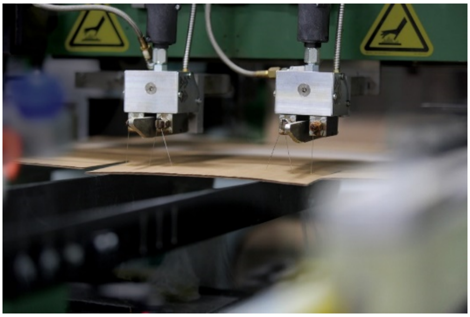
Conclusions. The considered model and methodology of numerical modeling of the strength of hot-melt adhesive joints provide the ability to predict the necessary and sufficient values of their strength.

Introduction

The technology of joining with hot-melt adhesive material is widely used in the chemical, food, and textile industries for forming joints in cardboard, paper, polymer, and combined packaging (Brockmann et al., 2008). This type of joint is used for joining and sealing various flexible and semi-rigid packages, such as those for flour, building bulk materials, confectionery products, and applying labels. Examples of the use of hot-melt adhesive joining are shown in Figure 1.

a

b



c

d

Figure 1. Examples of hot-melt adhesive use
a – manual application;
b – semi-automatic application;
c – automated equipment for application;
d – product packaged with hot-melt adhesive joints

Hot-melt adhesive joining has advantages compared to conventional glue. Traditional adhesive joints require a significant amount of time to achieve the planned strength, create solvent vapors in the workspace, and pose a risk of interaction with the packaged product. These disadvantages are absent when using hot-melt adhesive joining.

The use of hot-melt adhesive speeds up the process of labeling packaging, which directly affects productivity and production volumes. Additionally, hot-melt adhesive ensures effective and reliable label fixation, as it is resistant to external factors (moisture, heat, and cooling). In this case, the label will remain neat, and presentable, and not slip off during transportation.

Therefore, the task is to ensure the strength and reliability of the hot-melt adhesive bond to meet consumer demands during its use. Understanding the behavior of hot-melt adhesive joints during failure will allow the creation of high-quality joints in packaging elements.

The reliability of adhesive joints depends not only on the damage mechanisms but also on their ability to resist separation (Banea et al., 2015; Bennati et al., 2009; Campilho et al., 2013).

For example, in the works (Banea et al., 2009; 2010), the J-integral method is used to assess the strength of adhesive joints, which allows for determining the fracture toughness the driving force of crack propagation. For calculating flexible joined elements, it is advisable to consider the critical rate of energy release during deformation, taking into account large displacements (Zhao et al., 2016).

Mathematical models based on the adhesion zone method are most commonly used for modeling fracture processes (Stigh et al., 2016). Tasks of this type are solved using linear and nonlinear fracture mechanics. In most such mathematical models, the ratio of tensile and fracture stresses at the interface boundary is such that, as the interfacial distance increases, the adhesive strength at the interface reaches a maximum (crack initiation), then decreases, and afterward the crack propagates, leading to complete separation. The adhesion zone model simulates the fracture process by extending the concept of continuum mechanics, including the fracture zone, and using strength and energy parameters to characterize the separation process (Budzik et al., 2021; Leffler et al., 2007).

The reviewed works well describe the energy-force parameters of the fracture of rigid plate joints with a large contact surface area. However, they do not allow for a correct study of the fracture of joints in flexible materials with a narrow contact area, as is the case with flexible packaging.

Traditional mathematical models of fracture in the adhesion zone (De Moura et al., 2017; Valoroso et al., 2010) require experimental determination of the crack opening length as a function of the displacement of the sample edges. In the case of studying the fracture of hot-melt adhesive joints in flexible packaging materials, such measurements are difficult due to the narrow width of the bond zone and large displacements of the edges.

This study aims to numerically model the strength of hot-melt adhesive joints in flexible packaging materials to predict the opening force. This will allow for achieving consumer-friendly packaging joint strength, while also preventing unintentional self-unsealing.

Materials and methods

Materials

For the experimental study of tensile strength, three types of packaging materials were used – offset paper, cardboard, and polyethylene, which were subsequently bonded with hot-melt adhesive.

The mechanical properties of the materials used in the study are as follows:

- paper samples: elastic modulus – 2000 MPa, Poisson's ratio – 0.276;
- cardboard samples: elastic modulus – 1500 MPa, Poisson's ratio – 0.16;
- polyethylene samples: elastic modulus – 150 MPa, Poisson's ratio – 0.44.

Hot-melt adhesive from EVA-based material: elastic modulus – 90 MPa, tensile strength – 8 MPa, Poisson's ratio – 0.3.

The experimental study of the destruction process of hot-melt adhesive joints of paper, cardboard, and polyethylene samples was conducted according to the methodology outlined (Sokolskyi et al., 2020).

Methodology of numerical modeling

For the analysis of the fracture of thermoplastic adhesive joints, numerical modeling was performed using the finite element method to predict the initiation and propagation of fracture under static loads. The modeling of the double cantilever beam specimen, based on the adhesion zone methodology and fracture mechanics theory, accounts for irreversible failure at the interface, which is an advantage for modeling adhesive joints.

Figure 2 shows the general view of the finite element model. The model of the specimen consists of two strips of packaging material connected by a layer of hot-melt adhesive (red line), subjected to the action of two transverse symmetric forces. On the other side, the beam is rigidly fixed.

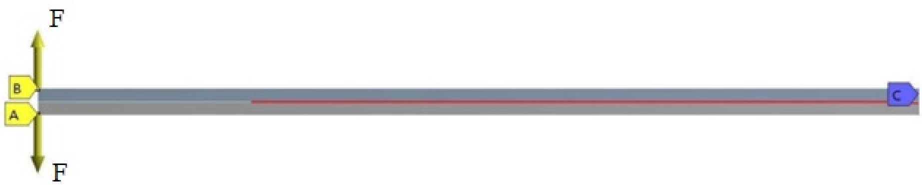


Figure 2. Finite element model of specimen bonded with hot-melt adhesive

Fracture of the adhesive occurs in Mode I (opening mode). It involves tensile stresses that lead to the crack formation (normal opening occurs in the field of normal stresses, and the displacement of the crack faces is perpendicular to the plane of the crack).

A numerical model was developed to study the behavior of the hot-melt adhesive joint during delamination, and a numerical calculation of the displacements and stresses occurring in the adhesive joint under tensile loading was performed.

A series of numerical experiments on fracture were conducted until the reaction values at the ends of the specimen matched those obtained during the experiment. By numerically selecting the values of the critical fracture energy, the threshold of bond strength energy is determined, and then, using this value, the force at the edges of the specimen, at which failure occurs, is calculated.

Experimental setup and procedure for conducting research

Tensile testing of bonded packaging material samples with hot-melt adhesive was conducted on the experimental setup shown in Figure 3 (Herasimenko et al., 2020).

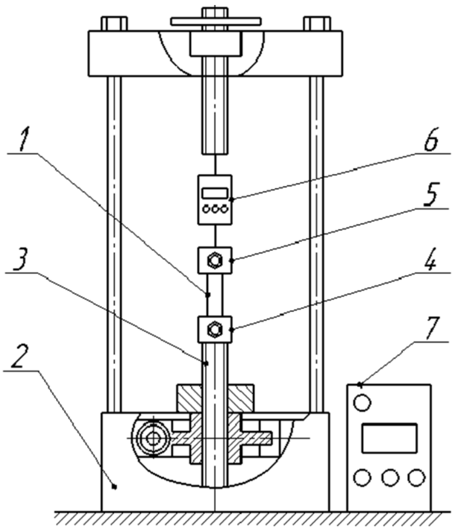


Figure 3. Experimental setup for tensile strength testing
1 – specimen; 2 – frame; 3 – tensile device; 4 – lower clamping jaws;
5 – upper clamping jaws; 6 – electronic dynamometer; 7 – control unit.

The experimental setup operates as follows. The test sample 1 is clamped between the lower 4 and upper 5 clamping jaws. A set tensile speed is established on the control unit 7. After activating the device, the lower jaw 4 moves downward at a constant speed and the electronic dynamometer 6 records the applied force. The displacement of the jaw is displayed on the indicator of the control unit 7.

The experiment was conducted as follows. First, the packaging material is bonded with hot-melt adhesive. The bonded strip of packaging material is then cut into individual samples. The test sample is clamped in the clamping jaws 4 and 5 of the setup (Fig. 3).

By stretching the sample at a set speed, we determine the force at the sample edges and plot its dependence on displacement.

Results and discussion

Mathematical model of the fracture process of the hot-melt adhesive joints

The geometry of the double cantilever beam is the most common test sample for analyzing the strength of adhesives and the delamination of composites. The double cantilever beam scheme is shown in Figure 4.

The specimen is rigidly fixed on one side, while symmetric forces are applied on the other side. The beam also has an initial crack, so the crack propagation continues in the opening mode.

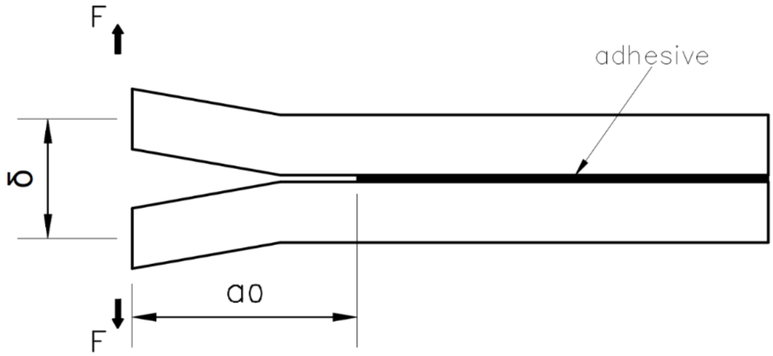


Figure 4. Scheme of the failure of the hot-melt adhesive bonded specimen

It is proposed to apply a mathematical model that allows the experimental determination of the fracture resistance of the joint to be used for calculating the maximum fracture force without measuring the crack length (Škec et al., 2018). It allows for avoiding the experimental determination of the crack opening length depending on the displacement of the sample edges for calculating the critical fracture energy. This model is proposed to be used for determining the opening force of the packaging, i.e., solving the inverse problem – numerical determination of the contact zone strength, from which the fracture force can be calculated.

For the mathematical description of the adhesive joint failure process, the adhesion zone model is used, in which the formation of failure is considered a gradual phenomenon, and the separation of surfaces occurs due to the deformation in the area of the failure initiation, which propagates along the adhesive layer.

To model the nonlinear elastic-plastic failure of a specimen with a central crack, we consider the crack propagation process based on the nonlinear adhesion zone model (Figure 5) (Škec et al., 2018).

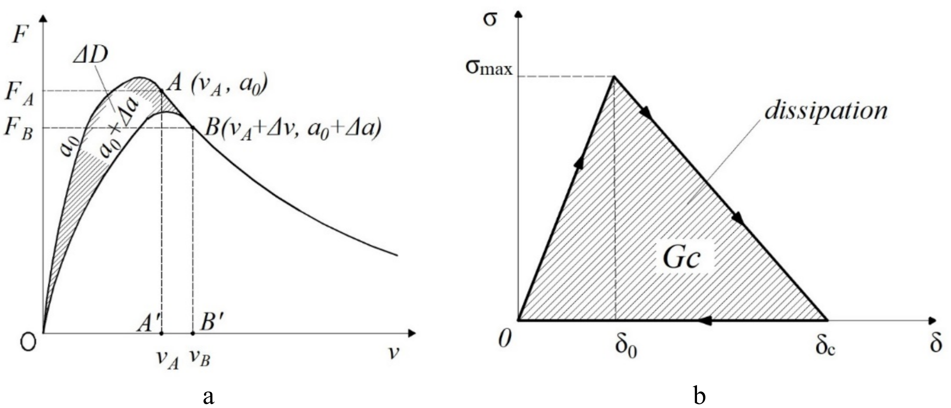


Figure 5. Behavior of the interface surface of the adhesion zone
a – dependence of the reaction force on the displacement;
b – equivalent adhesion zone law for the damaged point.

In these figures: F – reaction force at the edges, N; v – displacement vector, mm; a – crack opening length, mm; D – dissipation energy, J; σ – stress, Pa; G_c – critical energy release rate, J/m²; δ – relative displacement.

This model assumes that when the maximum stress $\sigma_{\max}$ is reached on the interface surface, plasticity zones form, leading to unloading in the local area of the specimen material.

The graphical representation of the power balance, shown in Figure 5a, illustrates the values of energy and its increment as the crack-opening zone propagates from the initial position a_0 to the new position $a_0 + \Delta a$. Point A corresponds to the displacement v_A and force F_A at which the crack-opening zone begins to propagate. At point A, the crack-opening zone extends by Δa, accompanied by an increase in displacement v_A from v_B and a decrease in force from F_A to F_B. The shaded area represents the increment in dissipation energy ΔD during the failure process.

Figure 5b illustrates that the propagation of the separation zone essentially involves the material failure at the tip of this zone, accompanied by energy dissipation when the deformation reaches the critical value $\delta = \delta_c$. While $\delta < \delta_c$, no energy is dissipated, and the stress increases linearly. When the separation zone propagates, the stress at its tip decreases from $\sigma_{\max}$ to zero, and the reaction force at the edges also decreases.

For this type of specimen deformation, the system's state is determined by the specified displacements and the crack length. In this case, the total potential energy can be expressed as a function of v and a.

In general form, the rate of change of the total potential energy $\hat{\Pi}$ is equal to the mechanical energy $\dot{\mathrm{W}}$ transferred to the solid body, taking into account the dissipation energy $\dot{D}$:

$$\dot{\hat{\Pi}} = \dot{\mathrm{W}} - \dot{D},$$

where the dot denotes the derivative with respect to t; $\dot{\mathrm{W}}$ is the mechanical energy, J; $\dot{D}$ is the dissipation energy, J.

From the perspective of thermodynamics, the equation takes the form of an inequality:

$$\dot{D} = \dot{W} - \dot{\hat{\Pi}} = \left(F - \frac{\partial \Pi}{\partial v} \right) \dot{v} - \frac{\partial \Pi}{\partial a} \dot{a} \geq 0 \text{ for all } \dot{v} \text{ i } \dot{a}.$$

where F is the reaction force, N.

Moreover, $-\partial \Pi / \partial a$ is a thermodynamic variable. Since $-\partial \Pi / \partial a \leq 0$ and $\dot{a} \geq 0$ it is necessary for the dissipation energy $\dot{D}$ to be non-negative. In this case, the rate of energy G release:

$$G = -\frac{1}{b} \frac{\partial \Pi}{\partial a} \quad (\dot{a} > 0).$$

Within the framework of the Euler–Bernoulli hypothesis, the total potential energy is given by:

$$\Pi_v = \frac{3EIv^2}{4a_{eq}^3}$$

where E is the modulus of elasticity, Pa; $I = bh^3/12$ is the moment of inertia of the cross-sectional area of each of the connected parts of the double cantilever beam, mm[4]; a_{eq} is the equivalent crack length, mm.

The equivalent length of the failure zone:

$$a_{eq} = \sqrt[3]{\frac{3\nu EI}{2F}}$$

The critical fracture energy:

$$G_C = \frac{F^2 a_{eq}^2}{bEI} \quad (1)$$

where b is the width of the specimen, mm.

The presented mathematical model allows for determining the critical fracture energy without considering the experimental value of the crack opening length as a function of the displacement of the sample edges.

The applied mathematical model allows using the experimental determination of the fracture resistance of the joint to calculate the maximum fracture force without measuring the crack length. Figure 6 shows the distribution of displacements and stresses in the testing model of the bonded paper specimen under tensile testing.

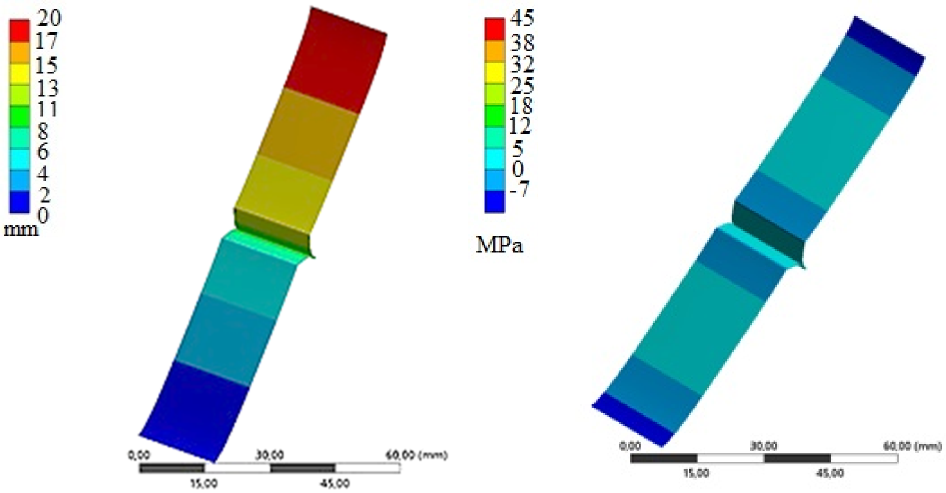


Figure 6. Model of tensile testing of the bonded paper sample:
a – distribution of displacements; b – distribution of stresses

From Figure 6, it is evident that at a displacement of 10 mm, the stress values at the edges are 14.2 MPa.

Figure 7 shows the graphs of the dependence of the force at the sample edges on the displacement for experimental values and those obtained from numerical modeling.

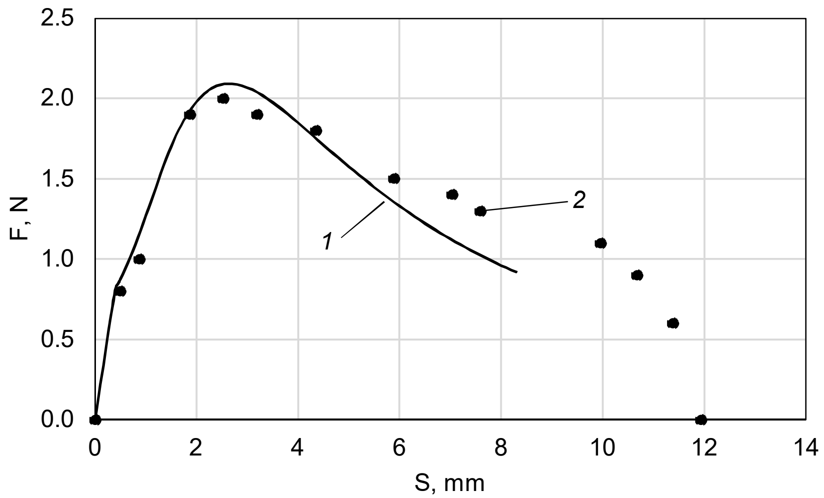


Figure 7. Dependencies of force at edges of paper sample on displacement
1 – modeling; 2 – experiment.

A comparison of the numerical calculations with the experimental values (Figure 7) shows almost complete agreement. The maximum force occurs at a displacement of 2-3 mm from the start of the crack opening, and then it gradually decreases. The total crack-opening force is 0.1 N/mm.

As the research results show (Millán et al., 2016; Xu et al., 2017), rigid material specimens, such as metal and composite plates, are typically studied. However, the shape of the 'force-displacement' curves qualitatively reproduces for the flexible packaging materials we investigated.

When the maximum stress is reached on the interface, plastic zones form, leading to unloading in the local area of the specimen material. As the joint continues to fracture, the tensile forces gradually decrease.

Figure 8 shows the distribution of displacements and stresses in the testing model of the bonded cardboard specimen under tensile testing.

From Figure 8, it can be seen that at a displacement of 10 mm, the stress at the edges is 10.08 MPa.

Figure 9 shows the graphs of the dependence of the force at the sample edges on the displacement for experimental values and those obtained from numerical modeling for cardboard samples.

The maximum force of 4.3 N occurs at a displacement of 5 – 6 mm from the start of the crack opening, and then it gradually decreases. The total crack-opening force is 0.22 N/mm. For the maximum force value, the discrepancy between the experimental data and numerical calculations is 7%, which is acceptable.

The fracture studies of hot-melt adhesive joints in cardboard materials are also described in (Hallbäck et al., 2014; Korin et al., 2007). The results obtained for slightly different cardboard materials and adhesives show qualitative agreement with the data obtained in this work.

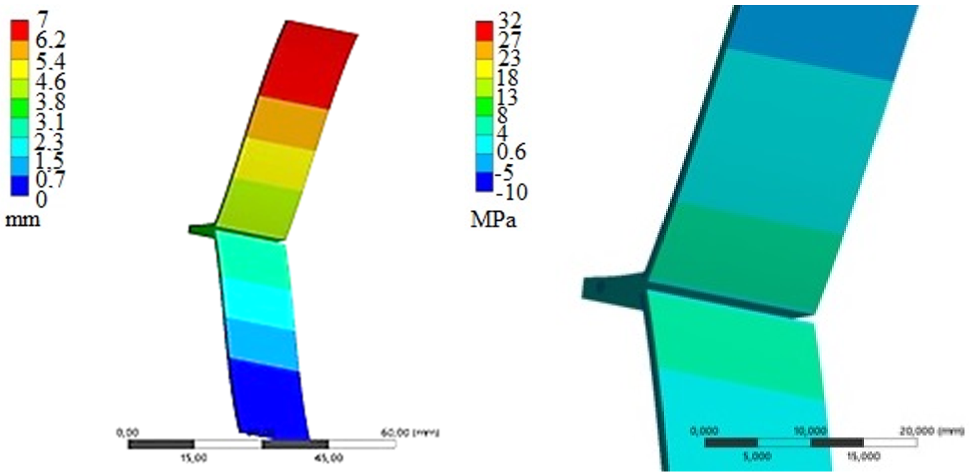


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Figure 8. Model of tensile testing of the bonded cardboard sample
a – distribution of displacements; b – distribution of stresses.

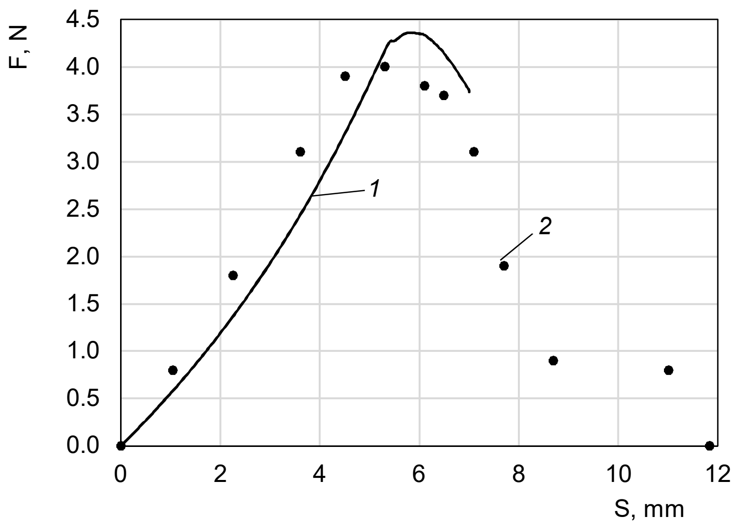

Figure 9. Dependencies of force at the edges of the cardboard sample on displacement
1 – modeling; 2 – experiment

Figure 10 shows the distribution of displacements and stresses in the model of tensile testing of the bonded polyethylene sample.

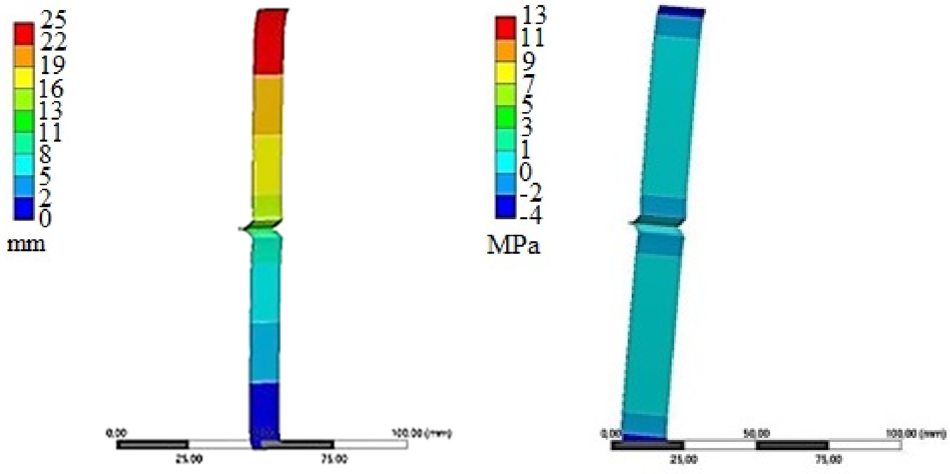

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Figure 10. Model of tensile testing of the bonded polyethylene sample:
a – distribution of displacements; b – distribution of stresses

From Figure 10, it can be seen that at a displacement of 10 mm, the stress value at the edges is 4.13 MPa.

Figure 11 shows the graphs of the dependence of the force at the sample edges on displacement for experimental values and those obtained from numerical calculations for polyethylene samples.

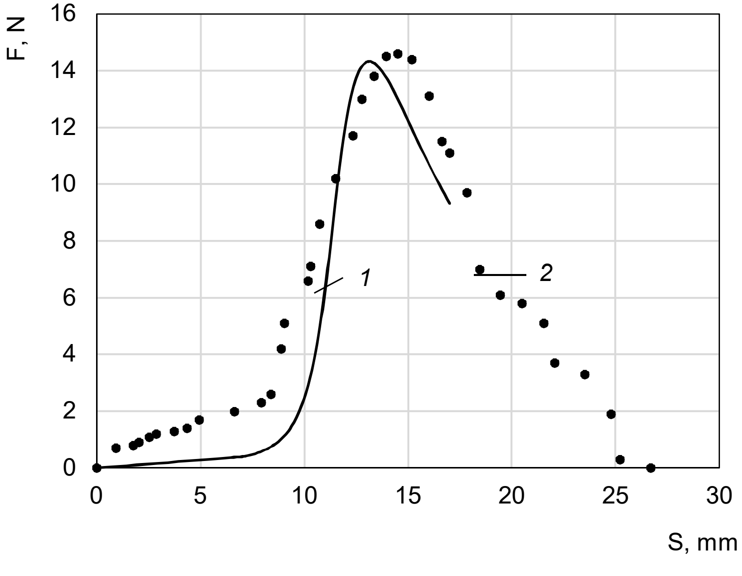

Figure 11 – Dependencies of force at the edges of the polyethylene sample on displacement:
1 – modeling; 2 – experiment.

The experimental curves in Figures 7, 9, and 11 qualitatively correspond to the curve shown in Figure 5a. That is, during stretching, the resistance force increases to a maximum, at which point the joint begins to fracture, and subsequently, with a further displacement of the edges, the fracture zone increases with a gradual decrease in forces until complete separation.

The maximum force of approximately 15 N occurs when the displacement is 12 – 13 mm from the beginning of the bond separation, and then it gradually decreases. The total opening force is 0.75 N/mm. For the maximum force value, the discrepancy between experimental data and numerical calculations is 2 %, which is within acceptable limits.

It has been established that the maximum force occurs at the beginning of the bond separation, and then it gradually decreases. As seen from the graphs, it requires twice as much force to break the hot-melt joint of the cardboard sample compared to the paper sample. The highest force value among the bonded samples is observed in polyethylene. This can be explained by the fact that during the bonding with hot-melt adhesive, some films undergo welding rather than gluing (a glue layer forms in the middle of the joint), meaning a chemical interaction of polymer macromolecules occurs, resulting in the disappearance of the interface between the bonded surfaces. An inseparable joint is formed, and further rupture occurs through the continuous material, as described in (Bennati et al., 2009; Waseem et al., 2014).

Numerical modeling of the strength of hot-melt adhesive joints allows for predicting the necessary and sufficient strength of adhesive joints for convenient disassembly by the consumer while ensuring the package's seal.

By numerically selecting the values of the critical fracture energy, it was possible to establish the strength limits of the bond energy, which illustrates good agreement between the theoretical and calculated graphs of the force-displacement dependence. From this value, the force at the edges of the sample at which it fractures can be calculated using the formula (1).

Conclusions

1. The considered model and method of numerical modeling of the strength of hot-melt adhesive joints allow for predicting the necessary and sufficient strength of the joints for convenient disassembly by the consumer, while also preventing self-unsealing.
2. The fracture of the hot-melt adhesive joint occurs after reaching its strength limit; the force value initially increases to the limit and then decreases until complete failure. Thus, it is possible to determine the maximum forces for opening packages made from different types of packaging materials, bonded under various conditions, for which the adhesive strength has been determined through modeling.
3. To assess the strength of the hot-melt adhesive joint, the dependencies of forces at the edges of paper, cardboard, and polyethylene samples on the displacement of the sample edges during stretching were obtained. It was established that, under the considered bonding conditions, the total opening force for paper materials is 0.1 N/mm, for cardboard – 0.22 N/mm, for polyethylene – 0.75 N/mm.

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