ASPECTS OF FRACTURE AND CUTTING
MECHANICS OF MATERIALS
Monograph

ASPECTS OF FRACTURE AND CUTTING MECHANICS OF MATERIALS

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Introduction

The monograph presents selected aspects of the mechanics of fracture and cutting the materials in realized technological processes. Among the others, propagation of cracks in brittle rock mass where symmetrical and asymmetrical disc cutting tools were used. Results of numerical analyses (FEM) are presented and cover aspect of run of crack propagation in the stratified rock material and selected composites. New possibilities of obtaining information regarding condition of tools cutting brittle rocks, including determination of features (discriminants) of power signal and head current and their selection due to possible usefulness in evaluation of condition of tools. Ways of using so called artificial intelligence were also discussed in order to increase accuracy of the results.
1. Selection and application of the optimal signal features used in evaluation of technical condition of cutting head tools of the longwall shearer

1.2. Introduction

Classification of the condition of cutters has been prepared using artificial neural networks available in two popular computer programs equipped with advanced options for creating neural networks - Matlab and Statistica. Creation of neural networks can be facilitated by Statistica software with option “Automatic Network Search” that makes achieving optimum neural network much faster.

Two types of neural networks were considered: MLP (Multilayer Perceptron) and RBF (RadialBasisFunction). Better results were obtained for MLP network and only they are presented in this paper.

Determination of condition of technical objects is usually realized using signal features. There are a few dozen of such statistic features (measures) and often in case of given class of objects special features are created. Using all possible features can make obtaining proper information regarding object condition more difficult. It is caused by a fact that some features can contain the same information and do not exhibit changes together with changing condition of a machine or exhibit varying tendency. That is why a person responsible for diagnosing can be unable to make unequivocal decision. Moreover, if one uses neural classifier, using too large amount of variables will cause longer computation time and error value can be higher. One has to emphasise that increasing number of variables results in nonlinear increase of number of cases required for neural network training and amount of data is often not so large.

Selection of the optimal features can be subjectively performed by an operator using own experience with given group of machines by selection optimal features or with aid of an algorithm. Different methods of computing feature importance can be used – from simple criteria to more sophisticated algorithms. In this work we used an algorithm presented in works of Lei [1] and Yang [2]. Value of each measure is computed in six steps and considered number of device states can be arbitrary. Obtained results are normalized with

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reference to the most important of them and lie within a 0-1 range. The larger value the more important the measure is. Computational method is objective and fast – it shortens the time of preparing diagnosing system.

1.2. Description of test stand and subject of investigation

Investigation has been realized for the tools installed in groups on multi-tool head. Measurements were performed for sharp and partially blunt cutters – power signals and cutting moment were registered in order to obtain sufficiently large base of the signals. Typical course of signals registered on the cutting head drive shaft is shown in Fig. 1.

![Fig.1 Anti-torque of multi-tool head operation versus time](image)

The stand consists of driving assembly (Fig. 2), feed assembly of the model solid with control systems and measurement and control assemblies. The feed was realized using hydraulic servo-motors by shifting model rock perpendicularly to the head rotation axis. Adjustment of the feed speed was realized using flow control in the hydraulic system.
Multi-tool head with 1400mm diameter was used in the tests. It was equipped with 39 cutters (including 18 on the cutting disk and rest on three plates. The tools were uniformly installed on the head perimeter as shown in Fig. 3.

Investigated objects – cutters currently used in mining industry (Fig. 4).
Empirical tests resulted in obtaining power and cutting torque time courses (Fig. 5.) for the head equipped with sharp and partially blunt tools.

Fig. 5. Time courses of the cutting power for the multi-tool head with radial cutters

1.3. Selection of the signal features

For the analyzed power and torque signals 12 signal features were computed:

1. Average
2. Mediana
3. Root Mean Square
4. Signal power
5. Peak value
6. Peak-to-peak value
7. Kurtosis
8. Crest factor
9. Pulse factor
10. Backlash factor
11. Variance
12. Standard deviation

Using algorithm [1, 2] importance of the features for the two signals were computed (Fig. 6). Three the most informative features common for power and torque signals were selected: average value, RMS and signal power. These features were used in neural networks training.

![Fig. 6. Measures classification results for the power signal](image)
1.4. Results

In case of the neural networks in Matlab software the results were are presented in 4 figures, separately for power and torque signals. In case of the Statistica software the results are summarized in two tables and one graph.

It is necessary to explain certain difference in nomenclature used in both programs since from Statistic ver. 8 data set that is not used in network training is called a ‘validation set’ and in Matlab a ‘test set’.

1.5. Numerical analysis for the cutting power signal

Fig. 8 presents network classification results for the training, validating, test and all data. The results were obtained using Matlab software module.
Fig. 8. Network classification results for the training, validating, test and all data

Confusion window contains four tables presenting results for the training, validating, test and all data sets. Green field (1.1 or 2.2 according to the fields numeration) presents number of cases classified correctly and red fields (1.2 or 2.1 according to the fields numeration) contains number of cases classified wrongly. Blue field (right bottom corner) contains summary for given group of data.

ROC curve graph on the horizontal axis contains falsepositive (1-specificity) and on the vertical axis contains truepositive (sensitivity). Falsepositive means probability (part) of sharp cutters that were classified as blunt and truepositives means probability (part) of cases of blunt tools classified as blunt. If the graph consists of two lines located in top left corner, all cases were classified correctly.
Fig. 9. Matlab window containing network training results

Fig. 10. Receiver Operating Characteristic curves
Fig. 11 presents the graph of artificial neural network training.

![Fig. 11. Graphs showing network training state](image)

Tables 1 and 2 present training parameters and classification results of the multilayer perceptron with 5 neurons in hidden layer. The tests were performed in Statistica package.

Table 1.1. Results and parameters of network training

<table>
<thead>
<tr>
<th>Network name</th>
<th>Quality (training)</th>
<th>Quality (testing)</th>
<th>Quality (validation)</th>
<th>Training algorithm</th>
<th>Error function</th>
<th>Activation (hidden)</th>
<th>Activation (output)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLP 3-5-2</td>
<td>82,54</td>
<td>74,07</td>
<td>88,89</td>
<td>BFGS</td>
<td>SOS</td>
<td>Sinus</td>
<td>Tanh</td>
</tr>
</tbody>
</table>

Table 1.2. Classification of the cutting tools condition - summary

<table>
<thead>
<tr>
<th>Classification summary. Tests: Training, Test, Validation</th>
<th>Zmn4-0</th>
<th>Zmn4-1</th>
<th>Zmn4-All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Together</td>
<td>90,00</td>
<td>90,00</td>
<td>180,00</td>
</tr>
<tr>
<td>Correct</td>
<td>68,00</td>
<td>80,00</td>
<td>148,00</td>
</tr>
<tr>
<td>Incorrect</td>
<td>22,00</td>
<td>10,00</td>
<td>32,00</td>
</tr>
<tr>
<td>Correct (%)</td>
<td>75,55</td>
<td>88,89</td>
<td>82,22</td>
</tr>
<tr>
<td>Incorrect (%)</td>
<td>24,44</td>
<td>11,11</td>
<td>17,77</td>
</tr>
</tbody>
</table>
Fig. 12 presents ROC curve for MLP 3-5-2 network.

![ROC curve](image1.png)

**Fig. 12. ROC curves (Receiver Operating Characteristic)**

1.6. Numerical analysis for the cutting torque signal

Figures 13-15 present results of the tests performed for the cutting torque moment in the Matlab package. Results are presented similarly as in case of the results for cutting power in chapter 4.1.

![Network classification results](image2.png)

**Fig. 13. Network classification results for the training, validating, test and all data.**
Fig. 14. Matlab window containing network training results.

Fig. 15. ROC curves (Receiver Operating Characteristic)
Fig. 16. Graphs showing network training state

Tables 1 and 2 presents training results and classification statistics.

Table 3. Results and parameters of network training

<table>
<thead>
<tr>
<th>Network name</th>
<th>Quality (training)</th>
<th>Quality (testing)</th>
<th>Quality (validation)</th>
<th>Training algorithm</th>
<th>Error function</th>
<th>Activation (hidden)</th>
<th>Activation (output)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLP 3-3-2</td>
<td>91.27</td>
<td>88.89</td>
<td>88.89</td>
<td>BFGS 16</td>
<td>SOS</td>
<td>Exponential</td>
<td>Logistic</td>
</tr>
</tbody>
</table>
Table 4. Classification of the cutting tools condition - summary

<table>
<thead>
<tr>
<th>Classification summary. Tests: Training, Test, Validation</th>
<th>Zmn4-0</th>
<th>Zmn4-1</th>
<th>Zmn4-All</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLP 3-3-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Together</td>
<td>90,00</td>
<td>90,00</td>
<td>180,00</td>
</tr>
<tr>
<td>Correct</td>
<td>85,00</td>
<td>78,00</td>
<td>163,00</td>
</tr>
<tr>
<td>Incorrect</td>
<td>5,00</td>
<td>12,00</td>
<td>17,00</td>
</tr>
<tr>
<td>Correct (%)</td>
<td>94,44</td>
<td>86,67</td>
<td>90,5</td>
</tr>
<tr>
<td>Incorrect (%)</td>
<td>5,55</td>
<td>13,33</td>
<td>9,44</td>
</tr>
</tbody>
</table>

Fig. 17. ROC curves (Receiver Operating Characteristic)

Summary

Presented results show that method of selecting optimal signal features found to be efficient in evaluating condition of the cutters working on the multi-tool head. Numerical investigation performed for the cutting torque signal allowed obtaining higher efficiency of cutters classification than in case of cutting power course.
Obtained results of the analyses, both in case of Matlab and Statistica software that were used in the research gave satisfying, similar results. Classification correctness of the neural network reached approx. 90%.

Three the most informative features, common for the power and cutting torque signal were selected: average value, RMS value and signal power. It allowed testing a method that is general-purpose. Application of too many number of input variables could cause too precise adaptation to the particular case and loss of generalization capabilities.

Bibliography
2. Identification and automation of shafts machining

2.1. Introduction

Methods of building mathematical model (MM) of the control object significantly depend on the capacity of a priorical information available from the moment of starting investigating of the given object. Task of developing a model can be realized in two stages. In the first stage, basing on this a priorical information regarding physical processes occurring in technological process, structure of the object is developed. Usually, this model includes unknown parameters, which are hard or impossible to be found basing on a priorical data. Initial structural model can contain certain elements that are not necessary in next stages of MM development. During second stage, basing on the experimental tests, unknown parameters are defined and model structure is improved. In many cases it is possible to simplify initial model structure. Dynamic system (UD) of the machining process is a Technological system (UT) - OUPN i.e. machine tool with realized technological process (PT) of the turning processing.

2.2. Identification of dynamic system of cutting processing for shafts with control realized using longitudinal feed

Basic goal of developing model of turning process in designing control system is minimization of measurement-shape errors of the machined tools. Taking into account the fact, that main cause of these errors in case of longitudinal turning is elastic deformation of the technological system and due to functional dependence of cutting force, these parameters are to be considered as input values of controlling object (OS).

Turning process is nonlinear. However, due to assumed use of the model to control and, in particular, to realize a task of stabilizing cutting forces in time (where output variables change slightly) one can linearize nonlinear dependencies near statistic point of operation.

Basing on the analysis of cutting layer geometry, cutting forces, elastic properties, technological system and process of forming section area of cut surface with taking into account phenomenon of cutting “along trace”, a system of dependencies in an operator form describing dynamic features of the machining process is obtained (Fig. 1) [1,2].

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In turning process influence of machining traces on the process course is characteristic – it is so called cutting “along trace”. It occurs since the parameters of cut metal layer in a moment \( t \) are determined both by instantaneous position of
the edge and both by its coordinates in a moment of previous rotation of parts \( t - \tau \), i.e. in a moment delayed by time of one rotation.

Denotation of variables on the structural diagram are: \( s \) – Laplace transformation operator, \( F_f \) – feeding component of cutting force, \( F_c \) – main component, \( F_r \) – radial component, \( n_c \) – rotational speed of the speed part, \( v_l \) – speed of longitudinal feed, \( c_1 \) – material hardness, \( b_1 \) – processing allowance, \( \tau = l/n_c \) - delay.

Relations between value of elastic deformation and components of cutting forces in the operator form are described with linearized dependencies:

\[
\Delta g_i (s) = \Delta H_i (s) \Delta H_i (s), \quad i = \{x, y, z\},
\]

After taking into account that time constants of chip formation for different components of cutting forces do not differ much, we can assume:

\[
M_{x}(s)N_{x}(s) = M_{y}(s)N_{y}(s).
\]

Using above dependency, a function of object transition (after transformations) can be written for i-th component of cutting force in a following form:

\[
G_{v_f f}(s) = \frac{M_{i}(s)G_{f}(s)}{s[1 + N_{y}(s)H_{yy}(s) + G_{y}(s)[M_{x}(s)H_{xx}(s) + K_{x}M_{y}(s)H_{yy}(s)]]}.
\]

Assuming transition function of chip forming process in a form of non-periodic element with time constant \( T_c \) and assuming oscillating secondary element with constant \( T_{us} \) and attenuation coefficient \( \xi \) as a model of dynamic properties of control system we get:

\[
G_{v_f g}(s) = \frac{m_{i}(s)G_{x}(s)}{s[(T_c s + 1)(T_{us} s^2 + 2\xi T_{us} s + 1) + B_{i}G_{x}(s) + n_{y}h_{yy}]]}
\]

or, after taking into account (1):

\[
G_{v_f g}(s) = \frac{m_{i}h_{xx}(s)G_{x}(s)}{s[(T_c s + 1)(T_{us} s^2 + 2\xi T_{us} s + 1) + B_{i}G_{x}(s) + n_{y}h_{yy}]]}
\]

Due to the above, forming process of cut layer section is significantly affected by cutting “along trace” and by elastic deformation of the technological system. Process of forming section of cut layer can be described by a system of integral-differential equations with delayed argument. The variables characterizing section of cut layer depend on input variables and elastic deformations of the technological system.

### 2.3. Output mathematical model

Controlling activity, in a form of longitudinal feed, is used in the most effective way to optimize the processes of machining the parts with relatively
high rigidity. Preliminary analysis shows that in this case one can take into account only own susceptibilities of the elements of technological system.

According to the set of equations [1] and equations (2-4) the output diagram of the structure of control object can be presented in a form like in Fig. 1. It shows that current value of thickness of the section and its increment are determined by three components:

\[ \Delta a(s) = \Delta a_{vf}(s) - \Delta a_x(s) - \Delta a_y(s) \]

where: \( \Delta a_{vf} \) - a component that depends on the speed of longitudinal feed (width of the section of cut layer without taking into account elastic deformations), \( \Delta a_x \) and \( \Delta a_y \) - components conditioned by elastic deformations for X and Y coordinates.

Increment of a current value of section width depends on elastic deformations of the technological system for Y and Z coordinates.

In that way, in case of the considered MM it is characterized by the presence of internal closed circuits in its structure – they are conditioned by an influence of the elastic deformations on the elements of the section of cut layer and singularities of cutting “along trace”.

In the further analysis influence of elastic deformations for Z coordinate on the width of a section as insignificant. Considered structure can be transformed assuming speed of longitudinal feed as input value. Resulting form is shown in Fig. 2.

---

**Fig. 2. Structural diagram of the control object**

Equivalent transition functions marked in Fig. 2 as \( G_1(s), G_2(s), G_3(s) \) are equal to:

\[ \text{...} \]
\[ G_1(s) = -M_y(s)\frac{H_{yy}(s)}{1+N_y(s)H_{yy}(s)}, \]  
(6)

\[ G_2(s) = -G_r(s)M_x(s)H_{xx}(s), \]  
(7)

\[ G_3(s) = G_r(s)[K_{K_r} - N_x(s)H_{xx}(s)]. \]  
(8)

Transition function for the components of cutting forces, e.g. \( F_f \):

\[ G_{v_f F_x}(s) = \frac{\Delta F_f(s)}{\Delta v_f(s)} = \frac{G_r(s)[M_x(x) + G_1(s)N_x(s)]}{s[1-G_{sz}(s)]} \]  
(9)

The following diagram of indices has been assumed for (here and later) denoting coefficients of gain and transition functions. First letter index indicate input coefficient (in the given case \( v_i \)), second – output value (\( F \) – cutting force, \( g \) – elastic deformation), third (if necessary) shows component of a cutting force or elastic deformation \( i=\{x,y,z\} \). Transforming dependency for \( G_{v_f g_i}(s) \), and applying the last expression for its denominator, we obtain:

\[ G_{v_f g_i}(s) = \frac{m_x h_{ss} G_r(s)}{s[(T_f s + 1)(T_{uu(s)} s^2 + 2\xi T_{uu(s)} s + 1) + B_1 G_r(s) + n_y h_{yy}]} \]  
(10)

where \( B_1 = m_x h_x + K_{K_r} m_y h_y \)  
(11)

### 2.4. Analysis of the possibilities of simplifying mathematical models

An analysis of the obtained dependencies of transition function of the control object has been performed for their simplification. Mathematical model of the control object in a form of transition function (10) takes into account inertia of the chip formation process and elastic system together with delay caused by singularities of cutting “along trace”. Characteristic singularity of the mathematical model is presence of internal, closed circuit in its structure. Thus, it is important to investigate features of the closed circuit and analyze its stability.

Stability of the mentioned circuit is determined by so called “vibrostability” of the machine [3]. If the stability conditions are not met, during cutting in dynamic system self-excited vibrations occur. While developing mathematical model of the dynamic machines system it was assumed that “vibrostability” of the machines is ensured i.e. closed circuit is stable.

Relation between time constants of the elastic system \( T_{uu} \), chip formation process \( T \), and delay time \( \tau \) were investigated. Delay \( \tau \), inversely proportional to
the rotational speed of a part is not less than 0.1 to 0.2 s in case of lathes. For medium size machine tools rotational speed of a spindle is 2000 rpm, thus minimum $\tau$ value is 0.03 s. Own resonance frequencies of equivalent elastic system of a machine tool and of a part for medium size lathes are within a range of frequencies higher than 50 Hz, i.e. the largest equivalent time constant $T_{us}$ does not exceed 0.003 s. Computations of the time constant of chip formation show that in ordinary cutting conditions values of $T$ do not exceed 0.005 to 0.001 s hence delay $\tau$ in (10), contained in a transition function $G(\tau)$, exhibits the largest value and exceeds (by an order of magnitude) time constants $T_{us}$ and $T_{c}$ [1,2]. Properties of equivalent closed circuit (if its stability conditions are met) are determined mainly by an element with the highest inertia – in this case an element with transition function:

$$G_\tau(s)=1-e^{-s\tau}.$$  

In later part a possibility of neglecting “small” time constants regarding transition function of the investigated object was evaluated. In order to verify formed errors frequency domain was used – frequency characteristics.

Frequency characteristics of a model are obtained by substituting in (10) $s=j\omega$ and by using Euler’s formulas for exponential function:

$$e^{-j\omega\tau} = \cos \omega\tau - j \sin \omega\tau.$$  

After transformation of a dependency for amplitude characteristics (ACH) and phase characteristics (FCH) one can write:

$$A(\omega) = m_i h_{ij} \frac{2\sin(\frac{\omega\tau}{2})}{\omega \sqrt{C_1^2 + D_1^2}}, \phi(\omega) = -\frac{\omega\tau}{2} - \arctg \left(\frac{D_1}{C_1}\right),$$ \hspace{1cm} (12)

where:

$$C_1 = 1 + n_i h_{yy} + B_1 - B_1 \cos \omega\tau - (T_{us}^2 + 2\xi_T T_{us})\omega^2,$$

$$D_1 = B_1 \sin \omega\tau - (T_{c} + 2\xi_T T_{us})\omega - T_{us}^2 T_{c}\omega^3.$$  

Fig. 3 shows functions of frequency characteristics (dashed lines) $A_1(\omega)$, $L_1(\omega)$ and $\phi_1(\omega)$ of the mathematical model of output transition function (9) that were obtained from numerical calculations for the following data: $m_i n_i = 1$, $\tau=1$, $B_1 = 0.6$, $T_{us}/\tau = 0.1$, $T_{c}/\tau = 0.05$. Thanks to assumed unit values $m_i n_i$ and $\tau$, presented relations can be considered as generalized characteristics of the mathematical model in relative units. Their form does not depend on the particular values of the time constants but their ratio and coefficient $B_1$. An argument in frequency characteristics is relative frequency $\omega' = \omega/\omega_b$, where value $\omega_b = 1/\tau$ [1] is assumed as base frequency. Full lines in Fig. 3 show
characteristics of a simplified model \( A(\omega'), \varphi(\omega'), L(\omega') \), obtained by neglecting time constants of the elastic model and chip formation processes: \( T_u = T_c = 0 \).

Fig. 3. Frequency characteristics of mathematical model of a dynamic system
Analysis of the obtained relations show that output and approximated ACH and FCH are periodical functions of frequency. For the critical values of frequency \( \omega_k = \frac{2\pi}{\tau} \) (k=1,2,3, .......), amplitude characteristics assumes zero values and the coordinates of logarithmic amplitude characteristics \( L(\omega_k) \Rightarrow -\infty \). Phase shift reaches -180.

Reduction of the object equivalent gain coefficient to zero for the critical frequencies is explained by singularities of cutting “along trace”. In case of critical frequencies trajectory of blade motion on developed surface for current rotation remains equally distant to the trajectory of motion in previous rotation. Consequently, increment of section thickness, cutting forces and elastic deformations equals zero.

For frequencies higher than first critical \( \omega_1 = \frac{2\pi}{\tau} \) maximum value of \( A(\omega^*) \) does not exceed (0,08 to 0,18)A(0) with changing \( B_1 \) coefficient in a range 0,1 to 1. Logarithmic phase characteristic is a discontinuous, periodic function. Points of their discontinuity overlaps with critical values of the frequency. Values of the logarithmic phase characteristics of an approximated model change within a range from 0 to -\( \pi \).

Taking into account inertia of the chip formation process and elastic system leads to changing value of logarithmic amplitude characteristics and phase characteristics. Moreover, it leads to additional phase shifts value and to the first critical frequency the difference between output and approximated logarithmic phase characteristics does not exceed 3 to 4dB. In this range of frequencies deviation of approximated \( \varphi(\omega^*) \) phase characteristics from output \( \varphi_0(\omega^*) \) occurs only near critical frequency value. Within the range of frequencies higher than critical one deviation between phase characteristics is significant.

During synthesis of the corrective elements of the automatic control system the cut-off frequency is chosen on the left side of the first critical frequency of mathematical model of control object. It allows to consider frequency characteristics of the mathematical model limiting frequency range to smaller ones than first critical equal to \( 2\pi/\tau \). For the given frequency range, as performed analysis showed, inertia of the chip formation process and elastic deformation can be neglected without significant error and assume at the end:

\[
H_i(s) = h_i, M_i(s) = m_i, N_i(s) = n_i, C_i(s) = c_i, \quad (13)
\]

Then, the approximated dependencies of the object transition function for recognized control activity and for the output values in a form cutting forces and elastic deformations are as follows:

\[
G_{i,e}(s) = \frac{\Delta F_i(s)}{\Delta v_i(s)} = \frac{K_{n,e}G_i(s)}{s(1 + B G_i(s))} \quad (14)
\]
\[ G_{v,F}(s) = \frac{\Delta F(s)}{\Delta v_f(s)} = \frac{K_{v,F}}{s(1 + BG_f(s))} \]  \hspace{1cm} (15)

where:

\[ K_{v,F} = \frac{m}{1 + n h_{n} m} \quad K_{v,e} = K_{v,F} h_n \] \hspace{1cm} (16)

\[ B = \frac{m h + m h_1 K_s}{1 + n h_{n}} \] \hspace{1cm} (17)

In this way, while developing mathematical models for control over dynamic system of machine tools with met condition of “vibrostability” it is allowed to describe the properties of the elastic system and chip formation process with gain coefficient. It means that mentioned elements can be considered as proportional.

One has to note that dependency between output coordinates (components of the cutting force and elastic deformations) and intermediate coordinate – thickness of a cut layer \( \Delta a_{v_f} \) as an input is presented by transition function of the closed circuit:

\[ G_{z,F}(s) = \frac{\Delta F_i(s)}{\Delta a_{v_f}(s)} = \frac{m}{1 + n h_1} \cdot \frac{1}{1 + BG_F(s)} \] \hspace{1cm} (18)

\[ G_{z,g}(s) = \frac{\Delta g_i(s)}{\Delta a_{v_f}(s)} = \frac{m h_1}{1 + n h_1} \cdot \frac{1}{1 + BG_F(s)} \] \hspace{1cm} (19)

In rough processing, when values of \( B \) coefficient are larger than 0.1, in order to obtain simplified relations one has to use development of the exponential function into Pade series. Limitation to the first two components of the Pade series one obtains:

\[ G_{v,F}(s) = \frac{\Delta F(s)}{\Delta v_f(s)} = \frac{K_{v,F}}{(T_{o1}s + 1)(T_{o2}s + 1)} \] \hspace{1cm} (20)

\[ T_{o1,o2} = 0.5 \pi \left[ 0.5 + B \pm \sqrt{(0.5 + B)^2 - \frac{1}{3}} \right] \]

Empirical investigations showed that obtained simplified models ensure precision equal 15% to 20% of time constants evaluation [2].
2.5. Empirical investigation of the static and dynamic characteristics of machine dynamic system

Investigation of the dynamic characteristics was performed using methods of active experiment. In order to obtain time characteristics curves of output coordinates of the object during cutting the semi-finished product with blade were registered.

It is worth noting that a process of cutting product with a blade at constant values of longitudinal feed and rotational speed of a product can be considered as transient process for control value and as transient process for a disturbance. Simultaneously, first and second operation can be considered as abrupt if main cutting edge is parallel to the cut surface and thickness of the cut layer remains constant after cutting in.

Mentioned transient processes are characterized by zero initial conditions. Transient object characteristics for a disturbance with non-zero initial conditions would be registered during turning semi-finished products with abrupt change of allowance (Fig. 6).

![Fig. 6. Sketches of semi-fabricated products for determining transient function: a – controlling longitudinal feed, b – disturbance in a form of allowance](image)

During experimental tests a tangent component of cutting force as object output value. To its measurement two-component dynamometer was used. Tangent cutting force moves “movable” part of the force gauge (to which blade is fitted) with respect the solid part located on a support due to elastic deformations of an element with reduced section. Values of the elastic deformations were measured with inductive sensor of linear displacements. Results showed that value
of the displacement of "movable" part with respect to the solid one, thanks to high longitudinal and radial stiffness of the element with reduced section depends practically only on the tangent cutting force.

In order to register static characteristic of the mentioned dynamometer, the blade fitted in the device using special lifting tool was loaded with a force equivalent with equivalent direction to tangent cutting force. Thanks to that dynamometer gain coefficient was found and it was established that nonlinearity of its static characteristics does not exceed 2%. Dynamic characteristics of the gauge were obtained using oscillographic recording of curves of transient processes caused by increase and decrease of load. Inertia of the gauge, as shown by performed experiments, is smaller by an order of magnitude than inertia of an object what allows considering the device as proportional element.

![Fig. 7. Experimental transient characteristics of the control object](image)

In order to obtain indicator of the beginning of transient process during oscillographic recording exactly in a moment of cutting the blade into a semi-finished product, low voltage was delivered to the blade (isolated from grip) - second pole was connected to the machine body. Moment of contacting the edge and machined semi-finished product was detected by closing mentioned electrical circuit.
Example: Fig. 7 and 8 show oscillographs of the transient processes, obtained during experimental testing dynamic lathe system. First was obtained for cutting process in the following conditions: semi-finished product material - steel C45, blade Ti55Co6, blade normal angle $\kappa = 90^\circ$, cutting speed $v_c = 90$ m/min, cutting depth $a_p = 1$ mm, speed of longitudinal feed $v_f = 60$ mm/min, thickness of a cut layer in a stationary state $a = 0.2$ mm, value of tangent cutting force in a stationary state $F_{c0} = 350$ N, product rotation time $\tau = 0.2$ s, product diameter $d = 30$ mm. Calculation of the cutting gain coefficients (taking into account literature data) gives $m_x = 6.6 \times 10^6$ N/m, $m_y = 1.4 \times 10^6$ N/m. Susceptibility of the semi-finished product, as shown by calculations, can be neglected in this particular case. Using static characteristics (Fig. 4 and 5) it was determined: $h_{xx} = 1.5 \times 10^{-7}$ m/N, $h_{yy} = 6.6 \times 10^{-7}$ m/N. Value of the coefficient $B$, computed using formula (11), $B = 0.099$ and approximated mathematical model can be assumed in a form of integrating element with a transition function (20).

Response of an element to abrupt change of input value, as shown above, theoretically presents linearly increasing signal in time $\tau$ (curve 1 in Fig. 7). Real curve 2 of the output value is sufficiently close to the theoretical one; maximum deviation is 12%.

Fig. 8a shows transient characteristics obtained during cutting time in the following conditions: semi-finished product - steel C45, blade Ti55Co6, $\kappa = 45^\circ$, $v_c = 96$ m/min, $a_p = 1$ mm, $v_f = 100$ mm/min, $a = 0.2$ mm, value of tangent cutting force in a stationary state $F_{c0} = 1450$ N, $\tau = 0.12$ s. Similarly as above, cutting process gain and elastic system coefficients were found and value of coefficient $B = 1.2$ was calculated. Model (3.18) should be assumed as approximated one (it takes into account value of a $B$ parameter) in a form of non-periodic element of second order.

Time constants determined using equation (20) are equal $T_{o1} = 0.2$ s, $T_{o2} = 0.006$ s. Taking into account that second time constant of an object is smaller by an order of magnitude than the first one, it can be assumed in further calculations that $T_{ip} = T_{o1}$ and approximate experimental curve with exponent...
and establish time constant to be $T_{1e}=0.18\text{s}$ - as a time after which output value reaches 0.63 of its value in stationary state. Evaluation error of computed time constant is:

$$\delta = \frac{T_{1e} - T_{1p}}{T_{1e}} \cdot 100\% = -11\% \quad (21)$$

Fig. 8b shows oscillograph of object time characteristics obtained during processing of a product with abrupt change of cutting depth from $a_{p1}=1.5\text{mm}$ to $a_{p2}=3\text{mm}$, i.e. change of allowance by $\Delta a_p=1.5\text{mm}$. Semi-finished product - steel C45, bladeTi65Co6, $\kappa=45^\circ, v_c=98 \text{ m/min, } v_f =100 \text{ mm/min, } a=0.2 \text{ mm, } \tau=0.075\text{s}$, value of tangent cutting force in a stationary state $F'_{c0}=620\text{N}, F''_{c0}=1240\text{N}$. According to the dependency described above average computed coefficient value is $B=0.9$. Time characteristics was approximated with an exponent with computed time constant $T_{1p}=0.106\text{s}$. Transient process can be characterized with non-zero initial conditions and experimental value of a time constant according to formula (21) equals 6%.

Listing experimental and calculated curves of transient processes was performed according to the methodology described below. Experimental time characteristics were approximated according to the following formula:

$$F_c(t) = F_{c0} \left[ 1 - \exp(-t/T_{1e}) \right]$$

where: $F_{c0}$ - established output value or its increment, $T_{1e}$ – equivalent time constant determined basing on the oscillograph as a time, after which output value or its increment reaches 0.63 of value in stationary state. Found values of $T_{1e}$ were compared with computed $T_{1p}$ that were defined as time, after which computed transient characteristic, described by above dependencies, reaches 0.63 of value in stationary state. Relative values of $T_{1p}$ depend on $B$ coefficient and they can be determined basing on the curves shown in Fig. 9.
Fig. 9. Graphs for calculation of time constants $T_{01}$ of a control object

Given results were obtained during processing of semi-finished products made of steel C45 with a blade Ti15Co6 working at normal angles $45^\circ$ and $90^\circ$. Values of time constants given in Table 1 were calculated as averaged results of three or four obtained oscillographs in steady conditions.
Table 1. Listing of cutting parameters and experimental and calculated time
constants

<table>
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<tr>
<th>Nr</th>
<th>$\tau$ [s]</th>
<th>$\chi_r$</th>
<th>$V_c$ [m/s]</th>
<th>$a_p$ [mm]</th>
<th>a</th>
<th>$F_{e0}$ [N]</th>
<th>$T_{le}$ [s]</th>
<th>$T_{lp}$ [s]</th>
<th>$\delta$ [%]</th>
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<td>0.2</td>
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<td>0.55</td>
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<td>45</td>
<td>0.8</td>
<td>3.0</td>
<td>0.2</td>
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<td>0.7</td>
<td>0.625</td>
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Analytic determination of time constants was performed using values of the
gain coefficients corrected by performed experiments. Errors of the computed
time constants basically do not exceed 20%. Results of investigating
experimental object characteristics for controlling values in a form of speed of
longitudinal feed and spindle rotational speed together with disturbing value in a
form of allowance on a part perimeter show that mathematical models, obtained
after analytic analysis, are useful. Research confirmed introduced conclusion
about possibly wide range of changes in case of control object parameters.

Summary

Structure and parameters of a control object depend on processing
conditions of the machine tool. Time constants of a time object are mainly
affected by delay time $\tau$, depending on object rotational speed. Moreover, object
inertia depends on a value of B coefficient. Adjustment range of the rotational
speed of main motion drive in case of ordinary machines reaches 100 and more - in certain range it can change time constants of a control object.

Object gain coefficient, defined by delay time, parameters of a technological system, gain coefficients of cutting process and also can change by an order of magnitude. Simultaneously it is necessary to take into account that such wide ranges of changes of the parameters of machine dynamic systems characterize their operation in whole technological range. During realization of the part processing its rotational speed usually remains constant and changes of object parameters are caused mainly by changes of allowance what results in changed gain coefficients in cutting process. Moreover, variability of the dynamic properties of an object is affected by changes of parameters of elastic system along product axis what occurs when technological system includes non-rigid part.

Properties of the turning process like nonlinearity, variability of parameters, deterministic and accidental disturbances cause that effective controlling is not possible in case of ordinary adjustment systems. Results of research covering use of developed control models indicate that good quality control can be ensured by adapting algorithms.

Bibliography


3. Problems of rock cutting with disc tools

3.1. Introduction

Rapidly increasing demand for highly effective technologies of tunnelling (underground tunnels, engineering structures) realised often in hardly mineable grounds requires improving machine structures – especially cutting tools. The most common are rotary tangential cutting picks and disc tools. Rotational cutting picks exhibit significantly higher strength comparing to classic wedge tools, thus they are the most popular in equipping heads of shearers. Disc tools, due to different mechanism of rock mining, exhibit higher strength than rotational cutting picks. However, mechanism of chip elements loosening process is relatively insufficiently investigated. The tools are mainly used in TBM machines (full-face tunnelling) but in recent years there were trials of applying them in longwall shearers and roadheaders.

3.2. Rock loosening mechanism – disc tool

As one can assume, currently two technologies of loosening are distinguished in case of disc tools. First, tangential operation of asymmetrical disc on edge (Fig. 1a)[1]. In this case one can observe undercutting similar to classic cutting. This solution has been used in e.g. machines for mining very hard and abrasive formation of grounds (ARM 1100 shearer). Second way includes rotation of symmetrical disks initially pressed to the ground (Fig. 1b) with movement equal to scale value in each run (mounted e.g. on TBM-type shearer head).

In mentioned cases of operation different mechanisms of crushing the rock structure occur. However, nature of these processes is not fully known – that is why a lot of effort has been made to investigate mechanics of them.

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In case of symmetrical discs it is assumed that in initial penetration into even surface it is crushed (Fig. 2a) and crushes expand in a radial way. Increasing pressure of crushed ground in so called crushed zone contributes in creation and propagation of tensile stresses in the ground. They cause “tensile” cracks [3,4]. Between mentioned zone and solid ground some scientists assume existence of transition (contact) zone.

In order to achieve energetically optimal solution of the mining process it is necessary to maintain accurate relation between disc penetration depth and distances of successive runs (or spacing of disks operating together). Literature shows that optimal relation scale/penetration depth in case of symmetrical discs lies in relatively wide range (10÷20), depending mainly on the properties of mined ground.

In case of asymmetrical discs there is a series of interpretations of the rock crushing process. According to one of them (Fig. 3)[8], disc crushes rock with its edge only a little bit, causing generation of cracks by shearing the material at the beginning of destruction process. Further crack development associated to loosening larger chip element results from formation of tearing stresses.
Fig. 3. Operation of asymmetrical disk in case of soft ground [8]

Shearing and tearing process, from energetic point of view, is much more advantageous comparing to the process based more on crushing the material.

3.2.1. Cutting stratified grounds

Paradoxically, despite probably the largest part of mining practice, cutting stratified grounds is relatively weakly known. According to one of the interpretations (Fig. 5), e.g. [6], stratification of rocks significantly changes mechanism of chip elements loosening.

Fig. 4. Forming chip elements with symmetrical disc in a stratified ground [6]

Depending on the stratification direction, combination of strength parameters of the particular rock layers, binder between them and possible cracks different course of rock loosening is obtained. It also affects energy consumption in case of given process and other technological parameters. Influence of the foliation on chip creation with disc tools is additionally illustrated in Fig. 5.
As it is shown in the Figure above, operation of disc in case of mass stratified perpendicularly to the mined surface causes limited loosening and many cracks, but gaps rarely reach level of accessible surface. It results in disadvantageous energy consumption. Cutting ground stratified parallel to the mined surface increases horizontal range of the cracks (between discs) leading to increase amount of loosened element what improves energy efficiency.

However, the problem is more complicated in case of milling heads or heads of TBMs since cutting or boring direction of rock mass is varying (Fig. 6).

Fig. 6 shows that mining with TBM shearsers stratified grounds strongly depends on direction of stratification with respect to the axis of full-face shearer. If efficiency of mining pseudo isotropic dusty rocks as a reference, one can observe that mining rocks stratified in parallel way to the cut surface exhibit similar efficiency (relative efficiency coefficient – 100%). Mining rocks stratified perpendicularly to cut surface results in the lowest value of the coefficient i.e. 45÷55%.
Numerical simulations performed using Disctinct Element Method increases state of knowledge about mechanism of cracks penetration in stratified materials (Fig. 7). Results of investigation are very similar to the ones obtained using numerical simulations performed for rocks (e.g. [10]), since similar mechanisms of structure destruction were observed. As indicated in Fig. 7, direction of stratification significantly affects penetration indicators before tool edge.

Fig. 7. Influence of stratification direction on cracking the material attacked with a tool [14]

3.3. Numerical investigation of disc cutting process

Numerical investigation of the cutting process (mining) are performed mainly to achieve optimal spacing between disks and select the best disc geometry (maximum output, the smallest energy consumption) according to the local conditions of operation. Rapid development of computation methods (FEM, DEM) facilitate the analysis but they do not allow more exhaustive description of damaging the rock structure during operation of tools. Using Voronoi diagram, Coulomb – Mohr’s model for the elements and elastic-perfectly plastic Coulomb’s condition in the elements contact zone allow analyzing influence of tools spacing on the course of damaging the material by the disc for different movements of successive runs (Fig. 8). Damaging of the following sandstone structure was analyzed: cohesion 36MPa, \( R_c = 50 \text{MPa} \), \( R_t = 3.75 \text{MPa} \), \( E = 20 \text{GPa} \), friction angle 23°. Disc angle 90°. Material of the
elements (grains): $E=18\text{GPa}$, cohesion $49\text{MPa}$, friction angle $23^\circ$, $\nu=0.33$, $R_t=14.6\text{MPa}$. Parameters of binder: friction angle after damaging $19^\circ$, $R_t=7.3\text{MPa}$, cohesion $24.5\text{MPa}$, normal stiffness $195\text{GPa}$, tangent $97\text{GPa}$.

**Fig. 8. Simulation of disc operation in successive runs [15]**

The simulations show propagation of radial cracks and expansion and connecting of cracks leading to larger loosening between discs what is good representation of practical situations.

3D simulations performed by Jung-Woo Cho (et al. [9]), allow spatial analysis of the results (distribution of stresses, deformations) as illustrated in Fig. 9.

**Fig. 9. Cutting model and obtained distribution of material plastification and tensile stresses [9]**
Performed numerical research using FEM [11] for asymmetrical disc showed that in case of single runs optimal s/d ratio should be equal to 6. Taking into account parallel operation of the second disc, located symmetrically with respect to normal to the surface in a point where crack reaches the mined surface, one can approximately assume that optimal relation of discs penetration depths to their spacing (s/d) is close to 12 what is very close to the results obtained in practice and to the simulation results [9].

**Fig.10. Course of chip loosening, asymmetrical disc, s/d=6, isotropic material [11]**

Results of the numerical and empirical research presented above do not include research over cutting stratified ground. Authors of this paper perform numerical research – results are presented in separate paper [16].

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Bibliography


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4. Simulation of operation of disc cutting tool on stratified rocks

4.1. Introduction

Disc tools are one of the most popular mining tools that ensure achieving high efficiency, particularly in case of highly abrasive rocks exhibiting large compression strength (Fig. 1). They have been researched for years [2][3], both in Poland and abroad – mainly in case of so called symmetrical disks used in full-face shearsers (TBM) used in tunnelling.

Data available in the literature shows that significant factors of rock mining with disc tools are:
- Properties of the rock (e.g. compression strength, tensile strength),
- Disc geometry (disc angle, nose radius),
- Technological parameters of cutting process (cutting depth, i.e. depth of disc penetration into the ground, distance from previous disc run called cutting scale).

Fig. 1. Cutting head with mounted asymmetrical discs [1]

In case of so called asymmetrical discs, main factor that significantly affects mining process and that is relatively weakly known is disc orientation i.e. its setting regarding previous breakout made by a previous disc (located on the

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mining head spiral). This problem have been researched earlier by the authors [3] and some aspects of orientation of asymmetrical discs orientation have been developed.

4.2. Influence of direction of ground stratification

Series of investigations [4, 5, 6, 7, 8] show that rocks cutting process highly depends on their stratification. Dependence includes values of loosening forces, shape of propagating trajectory and chip range.

In case of simple crushing of rock samples the analyses performed by Pietruszczak et al. [5] shows that strength of stratified material depends on direction of foliation regarding applied load and reaches maximum value for approx. 45° angle as shown in fig. 2. In case of more complex rock cutting issues analyzed in the work [7], shape of mentioned dependency is slightly different (Fig. 3), since asymmetry caused by cutting direction can be easily observed – cutting direction was parallel to the layers inclined by $\beta=0^\circ$.

![Diagram showing influence of foliation angle on the value of compressive strength](image)

**Fig. 2. Influence of foliation angle on the value of compressive strength [5]**

Influence of ground stratification on parameters of disc cutting tool is still not deeply investigated and is intensively researched both empirically and using analytical and numerical methods [9].
Fig. 3. Maximum value of critical force depending on change of foliation angle [7]

The authors also work on this subject using numerical methods and tools tested earlier in matters connected with cutting of rock materials [3,6,7,10,11]. Numerical simulations using finite element method (FEM) were performed to answer the question regarding influence of the stratification inclination (foliation) on the loosening trajectory and forces necessary to obtain critical point.

4.3. Numerical simulations

The analysis takes into account operation of an asymmetrical disk with draft angle 30°, directed with base into earlier runs (mined surface) as it is shown in Fig. 4. The issue has been analyzed as two-dimensional state of strain in the plane of disc axial section, perpendicular to the direction of its reeling and both perpendicular to the bottom of the cut mined by the disc. Shape of the analyzed model corresponds to the one of cases of cutting homogenous ground described in previous work of the authors [3].
Fig. 4. FEM model for the rock affected by an asymmetrical disk, a) stratification parameters, b) dimensions and boundary conditions of FEM model

Rock strength parameters:
1. Stronger layer with thickness $a=12\text{mm}$
   - Young’s modulus $E=2,0\times10^4\text{MPa}$,
   - Poisson ratio $\nu=0,2$,
   - Compression strength $R_c=20\text{MPa}$,
   - Tensile strength $R_t= 2,0\text{MPa}$.
2. Weaker layer with thickness $b=4\text{mm}$:
   - Young’s modulus $E=1,0\times10^4\text{MPa}$,
   - Poisson ratio $\nu=0,22$,
   - Compression strength $R_c=5,0\text{MPa}$,
   - Tensile strength $R_t= 0,5\text{MPa}$.

Boundary conditions assumed in FEM model (Fig. 4b) include full fixing ($u_y=0$, $u_z=0$) at bottom edge of the model and blocking horizontal displacements ($u_y=0$) at both vertical edges. Disc reaction on the rock is represented by constant pressure applied to the cut edges. Analyzed models included layers inclinations: $\beta=0^\circ, 10^\circ, 20^\circ, 30^\circ, 45^\circ, 90^\circ, 135^\circ, 140^\circ, 150^\circ, 160^\circ, 170^\circ, 180^\circ$.

Numerical analysis was performed applying finite element method using own software CrackPath3[6,7,10] and selected modules of ALGOR package. Gap initiation criterion was assumed as $PJ$ criterion, proposed by J. Podgórski [12]. Computed results were visualised by ALGOR Sview module and shown in Fig. 5(a–f). The figures show shapes of loosenings and dependencies between $P_{kr}$ – force necessary to propagate the gap and $u_z(A)$ – horizontal displacement of $A$ point, marked in 4b with blue circle.
a) $\beta = 0^\circ$

b) $\beta = 10^\circ$

c) $\beta = 30^\circ$

d) $\beta = 90^\circ$
Fig. 5. Chip shapes and force-displacement dependency for different inclinations of stratification

As a reference, examples of rocks with homogenous strengths equal to $R_c=20\text{MPa}$ and $R_c=5\text{MPa}$ (equal to strengths of both layers shown in Fig. 4a) were analyzed as well. Results are presented in Fig. 6.
4.4. Influence of foliation angle on the loosening force

Analysis of the simulation results (Fig. 5,6) allows forming the following conclusion: shape of loosened chip strongly depends on the foliation direction. In the assume algorithm of crack simulation (called also “lost elements” method) trajectory of gap propagation depends on the geometry of FEM mesh. Values of the loosening forces depends also on mesh quality, particularly on the size of finite elements since the “lost elements” method averages value of material effort inside the element, thus increasing size of the elements decreases average values of stresses and material efforts.

Collecting maximum values of the loosening forces according to different foliation angles we can obtain dependency $P_{kr} - \beta$, which is shown in Fig 7. Maximum values of the forces were limited by 25N that can be concluded using graphs obtained for the reference models (Fig. 6).
The graph (Fig. 7) shows important conclusion – there is a small range of foliation angles ($\beta = 0^\circ \pm 40^\circ$ and $\beta = 140^\circ \pm 180^\circ$) at which loosening force is small, comparable to the forces loosening homogenous material of the weaker layer, other angles of foliation can be characterized by large loosening forces comparable to the forces loosening homogenous material of the stronger layer. Transition between both areas of forces is rapid and occurs within the range $\pm (40^\circ \pm 45^\circ)$.

**Summary**

Assumed way of simulating operation of asymmetrical disc is significant simplification of real process that is three-dimensional, thus distribution of stresses is in many areas different than analyzed in the present 2D analysis. Dependency of the FEM analysis results on the quality and geometry of grid causes that values of the loosening forces should be considered as preliminarily estimated. However, quality dependence between forces and changes of the foliation angle remain valid even in case of these estimations.

One of the more interesting observations visible after analyzing computational results is occurrence of two areas with clearly different values of loosening forces. Boundaries between those areas can be characterized with rapid change of value that is different comparing to observation of force changes in the issues of cutting stratified grounds (Fig. 3). Min. values of the loosening forces were observed at approx. $150^\circ$ foliation angle, max. values at angles larger than $45^\circ$ what is in accordance with observed maximum cutting force (Fig. 3) with different directions of cutting and loosening with disc taken into account (thus, different signs of foliation angles in both simulations).
Precise 3D simulations, taking into account fine remeshing (changes of the FE mesh) near crack tip and using data obtained from measurement of real cutting process in natural scale, should facilitate verification of observed values of forces and characteristics of the dependence $P_{kr} - \beta$.

**Acknowledgements**
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**Bibliography**


5. Fatigue strength of screw joints at loading variable

5.1. Stabilization of the connection

In the process of tightening the fastener screw is tight initial strength. This force should be large enough that the applied work load there was no loosening of the connector. Selection of proper fastening torque values, however, does not close the whole issue. An important problem is to stabilize the connection that is unchanging in the bolt axial force caused by the tightening of the appropriate moment, in the process of exploitation. Undermining preload forces can destabilize the call and it may be caused by:

1. Bolt elongation as a result of short-term forces for large values.
2. Deformation of the elements of thread and combined forces as a result of variable.
3. Relaxation of stresses in the screw and assembled parts while working in conditions of high temperature.
4. Loosening the nut and vibration.

In addition, there is a decrease in tension, depending on the number of loading cycles. The decrease of the initial tension increases with an increase in the number of pins connecting elements (Fig. 1).

![Graph showing change of stress with number of loading cycles](image)

**Fig.1. Change of the value of stress depending on the number compression elements [4] 1 – without washers separate, 2 – two washers separate, 3 – five washers separate. Horizontal axis – stress, vertical axis – number of loading cycles**

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Increasing the value of the initial stress increases the connectors (Fig. 2). But you can not tighten the connection too much, as it may cause to be felled or destroyed screw thread from the excess of reduced stress while stretching and twisting. Fall pre-tension force is related to the way threaded mechanical surface treatment (Fig. 3).

Fig. 3. Influence of the way of carrying screw area for stabilizations of skrew joint surrendered to variable stresses. [7]. 1 – rolling screw, 2 – cutting screw, 3 – cutting screw and then annealing. Horizontal axis – stress, vertical axis – number of loading cycles
During the rolling process the material cure-oriented structure and compressive stress have a direct impact on the increase in the strength of the thread in the static and dynamic loads.

In each case (Table 1) [5] thread rolled had a higher shear strength of about 25% for the bronze to about 38% of the nuts made of steel. Significant impact on the strength of threaded joints has surface roughness of the thread groove.

<table>
<thead>
<tr>
<th>Shearing stress $\tau$ [MPa]</th>
<th>Material</th>
<th>1H18N9T</th>
<th>C22</th>
<th>CuZn39Pb2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cutting</td>
<td>28</td>
<td>26</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>rolling</td>
<td>40</td>
<td>34</td>
<td>22</td>
</tr>
</tbody>
</table>

It was found that the limit cycle amplitude of the stress in the connector with thread rolled by about 50% compared with the thread heads. Changing the physical and mechanical properties of the surface layer is even more important for the fatigue strength than surface roughness. The resultant cold work during machining of the surface layer and fibrous construction metal structure substantially increases the cyclic strength of threaded joints.

**Fig.4.** Burnishing screw-tap M16 made joint similar to rolling screw

### 5.2. Effect of temperature

During the design of structures working in high temperatures should be carried out to check the calculation because of the long-term creep and fatigue [1]. At high temperatures, the materials have poor ductility and brittle destruction of the screws have character. In the case of variable bolt-bearing loads to be used alloy steels, which have high values of fatigue strength and
flow. High durability and flow ranges can be obtained for carbon steel and hardened using a temperature of 1113±10 K and drawing tempering at 573K. In carrying out the screws alloy steel to be used high tempering (773 - 823) K in order to obtain sufficiently high yield, which allows you to use them in case of complex loads. Effect of heat treatment on the number of loading cycles is shown in Fig. 5.

Research indicates that for short heating (20 min) strongly reduced strength of the bolt. Molybdenum bolts may maintain its long-term strength at temperatures $T \leq 1273$K and temporarily up to 1923K. In order to increase high-temperature creep resistance bolts they are covered with silicon. At higher temperatures the sensitivity to stress concentration and creep resistant steel castings is increasing rapidly, therefore rounding radii in outline line and the transition between the threaded rod and the head must be increased.

Fig. 4. Dependence of the amplitude of the stress on the number of loading cycles in case of applying thermal treatment (bolt M10×1, material 40H) [4]
Creep at normal temperature called the slow destruction occurs in brittle materials with low plasticity. The reasons for the slow destruction of the fragile high-steel screws are:

1- tightening torque is too large for the assembly, putting in the holes with interference, tightening the nut on the threaded output,

2- poor surface quality, small radius curves, the presence of corrosive, The strength calculation of the static load safety factor for creep - \( x = 1.4 - 2.5, \) when the long-term strength – \( x = 1.6 - 4 \)

5.3. Load of highly threaded joints

Basics causes fatigue failures threaded joints are reduced under the action of tightening force of variable loads, improper implementation of the technological process of threading, the use of improper heat treatment and prevent the strengthening of the surface object of the study described in [2, 4] M10 bolts were made of martensite steel. Research was conducted on the hydraulic pulsator busy cycle and asymmetric load \( (R_m = 600 \text{ MPa}) \) with load frequency 6 cycles / min. The base number of cycles used in the studies was \( N \geq 10^4 \) cycles. The results stress \( 
\sigma_N \) limit for a given life \( N = 10^4 \) cycles are shown in Table 2

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>Cycle of loading</th>
<th>Presence of the strain</th>
<th>( \sigma_N ) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>673</td>
<td>Pulsation</td>
<td>Without the strain</td>
<td>620</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strain</td>
<td>690</td>
</tr>
<tr>
<td></td>
<td>Asymmetrical</td>
<td>Without the strain</td>
<td>870</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strain</td>
<td>870</td>
</tr>
<tr>
<td>723</td>
<td>Pulsation</td>
<td>Without the strain</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strain</td>
<td>550</td>
</tr>
<tr>
<td>773</td>
<td>Pulsation</td>
<td>Without the strain</td>
<td>480</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strain</td>
<td>440</td>
</tr>
</tbody>
</table>

Conclusions regarding the durability of screws:

1. The maximum limit of endurance have screws in an asymmetric load cycle. It is 24% larger than the bolts tested at the busy cycle of the load (at 673 K)
2. Strengthening surface (shot peening) gave a positive effect only when the busy cycle loading at 673 K. The increase in fatigue limit screws for a given life was about 10%, and increase sustainability in relation to \( N = 10^4 \) cycles for the strained screws increased 1.3 fold.
3. At a temperature of 723 K and the durability of strain and without the strain screws is virtually identical, and a temperature of 773K durability reinforced
bolt appears to be less than 1.3 times without the strain. With increasing temperature from 673 to 773 K screws on the busy life cycle burden is reduced about 2.5 fold.

While other studies found that the asymmetric load cycle, when the volume reaches a maximum value of \( \sigma_{\text{max}} = (800 - 1000) \) MPa, no observed effect of strengthening the positive impact of even surface at 673 K, although the overall life cycle of bolts in such a case the burden is clearly greater than the pulsation cycle of the load. The results of observation of fatigue crack screws shown in Table 3.

<table>
<thead>
<tr>
<th>Temperature of examination [K]</th>
<th>Cycle of loading</th>
<th>Presence of the strain</th>
<th>% destruction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>At bolt head</td>
</tr>
<tr>
<td>673</td>
<td>Pulsation</td>
<td>Without the strain</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strain</td>
<td>87,5</td>
</tr>
<tr>
<td></td>
<td>Asymmetrical</td>
<td>Without the strain</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strain</td>
<td>16,7</td>
</tr>
<tr>
<td>723</td>
<td>Pulsation</td>
<td>Without the strain</td>
<td>66,7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strain</td>
<td>40</td>
</tr>
<tr>
<td>773</td>
<td>Pulsation</td>
<td>Without the strain</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strain</td>
<td>-</td>
</tr>
</tbody>
</table>

Destruction followed two screws cross: crossing at the head of the screws, the furrow of the first reel of thread.

Proposals for fracture of screws:

1. At a temperature of 673 K at the busy cycle of destruction screws without the strain load going down the most at the head of the screws was observed in individual cases, rupture of the threads. In the case of reinforced screws on thread destruction was not observed. In addition, screws without the strain which was destroyed on thread, also showed the presence of cracks in the transition at the head of screw.

2. During asymmetric load cycle without the strain bolts damaged and destroyed only on thread, although at all damaged screws after studies found the presence of cracks at the head of the screw.

3. At 723K, most without the strain screws were destroyed at the head. Cracks in this place had a screw, which was destroyed in the threads. After strengthening the basic type of destruction was the destruction of the threads, although these bolts were also found cracks in heads.

4. At 773K, all bolts were damaged only on thread, but on all the screws were also cracks in the heads.

Example of fatigue failures stud bolt used in the construction of a lift the size of M16 (Fig. 5), constructed in accordance with SAE standard. Frequent damage
(Fig. 6) bolts in the structure resulted in the need for replacement. Using new bolts, made in accordance with the guidelines according to standard ASTM A193. Breakthrough fatigue tests (Fig. 7.) Damaged screws. Microscopic analysis was carried out broken bolts on the cross and longitudinal diameter.

Results:
1. The area of final fracture (fracture ad hoc), was located between two areas of fatigue propagation, suggesting the presence of bending loads.
2. Additional crack formed between the strands of thread near the fracture area. This means that the screw is very sensitive to initiate fatigue.
3. Broken screw also has signs of chipping the core diameter (Fig. 7). Scaling, however, is permitted when the bolts work for such a burden.

![Fig. 5. Double – nutted bolt M16](image5)

![Fig.6. View from the side for the cracked double – nutted bolt](image6)

![Fig.7. Fatigue fracture of bolt](image7)
The results of chemical analysis.

The original screw contained less carbon than the required standards of SAE. A lower carbon content is likely to influence the reduction of material properties. Results of chemical analysis of the damaged screws and bolts made by the requirements of standard ASTM A193 / A also presented in Table 4 etching revealed the microstructure of the cross - coarse perlite in the structure of ferrite. Standard SAE standard requires that the screw is improved heat, resulting in what should have tempered martensite structure.

Martensite has higher mechanical properties such as yield strength and the strength and hardness, which increase its resistance to initiate fatigue. Defective bolts were not improved thermally. Their ferritic structure is a lower limit of endurance, which in turn contributed to reduced resistance to fatigue initiation. Bolts made according to the requirements of ASTM have a martensite structure which means that they have been quenched and tempered.

### Table 4. Chemical analysis of screws

<table>
<thead>
<tr>
<th>Element</th>
<th>Content in the exanimate bolt (%)</th>
<th>Content according to the standard SAE (%)</th>
<th>Content in the new bolt (%)</th>
<th>ASTM Standard B7 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.20</td>
<td>0.28-0.55</td>
<td>0.42</td>
<td>0.37-0.49</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.65</td>
<td>--</td>
<td>0.85</td>
<td>0.65-1.10</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.22</td>
<td>--</td>
<td>0.22</td>
<td>0.15-0.35</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.013</td>
<td>0.048 max.</td>
<td>0.015</td>
<td>0.035</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.011</td>
<td>0.058 max.</td>
<td>0.030</td>
<td>0.040</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.08</td>
<td>--</td>
<td>0.79</td>
<td>0.75-1.20</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.06</td>
<td>--</td>
<td>0.07</td>
<td>--</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.01</td>
<td>--</td>
<td>0.15</td>
<td>0.15-0.25</td>
</tr>
</tbody>
</table>

Tensile tests of bolts in order to compare with the standards. The results (Table 5) showed that the yield strength and tensile strength of the original bolt is only 60% required by the standards. Ownership of the new bolts were consistent with the standards and even slightly higher than the required

### 5.4. Tighten - up strength bolts with plastic deformation

Tighten - up strength bolts with plastic deformation of the static calculations show that an increase in bolt tension force to the limit of plastic deformation results in improving the performance of threaded connections. Followed by a more even load distribution on strings of thread and a decrease of
stress concentration in check (at the bottom of the thread.) Pin screw normally is subjected to tension and torsion, the stress values show oscillations with a frequency and amplitude of vibration caused by machines. Oscillations can lead to fatigue and, with suitably large values of stress, causing the process vibrocreep.

Table 5. Comparing the ownership of strenght bolts

<table>
<thead>
<tr>
<th></th>
<th>Original bolt</th>
<th>New bolt</th>
<th>Standard 5 SAE</th>
<th>Standard ASTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strenght (MPa)</td>
<td>640</td>
<td>1022</td>
<td>820</td>
<td>1000</td>
</tr>
<tr>
<td>Yield point (MPa)</td>
<td>427</td>
<td>934</td>
<td>640</td>
<td>960</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>26</td>
<td>20</td>
<td>min 16.</td>
<td>min 16.</td>
</tr>
</tbody>
</table>

Stability tests connections [6] were carried out with assumptions:
1 - M12 bolts tested were introduced in the state of elastic and plastic deformation by changing the torque,
2 – variable dynamic load-pulsing amplitude equal to 2 [mm] and frequency f = 6Hz,
3 - the tests were carried out until the crack registering the number of cycles.

Results:
1 - steel bolts class 8.8 has a small plastic deformation due to the strengthening and are mainly suitable for operation in the elastic,
2 - in terms of elastic, there was no permanent deformation caused vibrocreep,
3 - after loading the material beyond the elastic limit (plastic deformation ) and the imposition of cyclical changes in the value of stress, there is a permanent deformation caused vibrocreep; value of the strain decreases with time,
4 - longitudinal strain caused vibrocreep are for a given number of cycles the greater the larger the value of longitudinal stress and the increased value of the oscillation amplitude,
5 - the size of the initial plastic deformation of the material has no significant effect on the volume strain caused vibrocreep,
6 - the results of the fatigue life of bolts plastically deformed show more than 3-fold increase in fatigue life in relation to the screws fastened to elastic deformation.

In [4, 6] presented results of comparative studies stability threaded connections at different states of tension bolts in a changing dynamic loads at the load cycle zero - suppresion busy. The study was conducted over the bolts M12x1, 75 8.8, threaded its entire length when closing:
1. Torque PN-81 / M -82065
2. Moment that causes plastic deformation of the screws, in which case a tightening was performed using a gradient assuming that the decline in the value of tightening gradient of 50% in constant gradient indicates the achievement by the screw of the plastic deformation.

During the endurance tests carried out screws, threaded its entire length, often bursting bolts at the head of the first reel of thread. Many cracks occurred in the middle of the thread at a relatively low number of cycles leading to fracture. The largest number of cycles to crack reached screws plastic deformation. Breaking in the threads in the middle nut bolts appeared in a several times higher fatigue life. Stress values in the tested screws were relatively large, hence the low number of cycles to fatigue cracks. Tests have shown a significant advantage of the fatigue life of the plastic deformation of the screws compared with screws tightening by the date specified in PN.

Bibliography

6. FE modeling of dynamics of impact damaged sandwich plates with intermittent CONTACT in detached fragments

6.1. Introduction

Many of modern aircraft and spacecraft designs typically include sandwich materials consisting of thin stiff face sheets and a soft lightweight core. This type of the material structural concept seems very susceptible to damage caused by out-of-plane loading such as low-velocity impact events. Therefore, these high performance structures must be designed so that to sustain in-service static and dynamic loads with barely visible impact damage (BVID). On the other hand, because BVID may lead to the strength reduction up to 50% with respect to an intact structure [1], this damage has to be detected as early as possible. Vibration-based non-destructive monitoring techniques, using changes in vibration characteristics are very suitable for identification of BVID in highly heterogeneous sandwich materials [2]. Consequently, the investigation of sandwich structures, containing impact-induced damage, in dynamic environment is of primary importance for their reliability.

A huge number of papers in the open literature are being devoted for predicting the residual compression strength of impacted sandwich specimens, e.g. [3]. In such articles, analytical models, describing the global buckling and the local buckling in the face sheet at the place of impact and core-to-face sheet debonding growth failure mode have been typically developed and discussed on the basis of experimental results following from axial compression tests. Thereafter, the suggested damage models are being incorporated into the failure analyses for modeling strength responses of engineering structural components such as beams, plates and shells by using mostly the finite element method.

Dynamics of impacted sandwich panels is less studied and, in essence, this task is reduced to studying the dynamic behaviors of sandwich beams and plates with prescribed either a partially debonding interface or a locally damaged core. In the earliest papers devoted to this topic, authors modeled the beam by the split model that comprises of four Timoshenko beams connected at the detached edges. The ‘free mode model’, neglecting the overlapping between freely vibrating adjacent layers with and without the bending-extension coupling and 'constrain mode model’ that implies for such debonded parts the same flexural deformations were developed for studying free vibrations. The recently reported

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beam models, improved by inserting virtual springs into the open interface allow including the both models developed earlier as special cases, e.g. [4]. By adopting similar spring models the finite element method was used in [5] for calculation of modal characteristics of sandwich plates with debonding. The influence of the size, location and form of the debonding zone as well as various boundary conditions and core types on natural frequencies and mode shapes were examined. The extension of this FE modeling technique on sandwich plates with multiple debonding zones was considered in [6]. The high-order theory approach was applied to derive the equations of motion and to investigate free vibrations of sandwich beams with a locally damaged core in [7].

In general, vibrations of sandwich panels with the imperfect core-to-face sheet interface are accompanied by intermittent contact between the detached fragments. Therefore, a better understanding of the dynamic behavior of such panels must include a contact-impact phenomenon at the damaged interface. The free vibration behavior of simply supported debonded sandwich beams taking into account interaction between the detached parts was analytically studied in [8]. The use of this approach for studying the transient dynamic response of such sandwich beams was proposed in [9]. Numerical FE analysis of the forced and transient responses of beams with detached adjacent layers including the contact effect is presented in [10]. The nonlinear FE dynamic analysis involving contact-impact conditions for detection of interfacial cracks in sandwich beams was carried out in [11].

The objective of this paper is to develop a FE analysis tool for examining the dynamic behavior of sandwich plates with post-impact damage state. The intermittent contact behavior in detached fragments at the damaged site is paid special attention.

6.2. Theory and FE Model Development

According to the experimental findings, e.g. [3], a FE model of a sandwich plate with low-velocity impact damage has to capture a combination of failure modes among of which face sheet damage, core crushing and core-to-face sheet debonding are primary. It should be noted that in the case of BVID the face sheet remains almost undamaged and core crushing and debonding occur only. In this study, it was assumed that a sandwich plate at the center was struck by a spherical object. Consequently, a circular region will further define the form of the impact-induced damage in the sandwich plate as well as the impacted face sheet and the crushed core will form residual indentations corresponding to the part of the regular spherical surface. Fig. 1 shows the key parameters of the representative cross-section of the sandwich specimen impacted in the above mentioned way, which include the peak depth of the residual face sheet indentation, $\delta_{dent}$, the peak depth associated with core crushing, $\delta_c$, and the radii of the planar dimension of the damaged face sheet $R_{dent}$ and the crushed core.
In the current method, a FE model is being developed to represent impact-damaged sandwich plates. The commercial FE code ABAQUS [12] is used to perform the FE analysis. The face sheets are discretized with 8-node reduced integrated continuum shell elements, SC8R and the core is modeled using 8-node linear solid elements with incompatible mode, C3D8I, which are available in ABAQUS code. The general mesh of the damaged sandwich plate was subdivided into three different zones: the fine meshed impacted region, the next zone surrounding the impacted region with gradually decreased mesh density, and the coarse meshed last zone introduced in order to minimize a CPU time. On the basis of the results of the convergence analysis, conducted previously before the base calculations, the mesh density was accepted with the size of the characteristic element length about 5 mm. This size was selected as optimum between the computational cost and calculation accuracy. Moreover, it is worth to notice that the smaller is the element size, the lesser is the integration time step in the dynamic analysis. A typical FE mesh and cross-section details at the impacted site are given in Fig. 2a and b, respectively.

The damages, imparted into the face sheet and the core as a result of the impact event are represented by reducing of elastic properties of the FE elements along the damaged regions. Appropriate reduction coefficients are used for this
purpose. In Fig. 2b such regions are outlined in the different ways. The residual indentations of the impacted face sheet and the crushed core as well as the cavity, $\delta_{cav}$, developed between these fragments as a consequence of differences in the indentation depths are described on the basis of experimental results taken from the open literature to simulate them as close as possible to the real physical cases.

While, the finite element approach is used, the dynamic response of the impact-damaged sandwich plate, including the effect of intermittent contact in the detached fragments and assuming that the debonding front is not advancing during oscillations can be obtained by solving the following discretized system of motion equations:

$$\mathbf{M}\ddot{\mathbf{U}}(t) + \mathbf{C}\dot{\mathbf{U}}(t) + \mathbf{K}\mathbf{U}(t) = \mathbf{F}(t), \quad (1)$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the global mass, damping and stiffness matrices obtained by the assembly procedure, $\mathbf{U}(t)$, $\dot{\mathbf{U}}(t)$ and $\ddot{\mathbf{U}}(t)$ are the vectors of unknown nodal displacements, velocities and accelerations, respectively, $\mathbf{F}(t)$ is the vector of nodal forces included the known external forces and the normal and tangential contact forces calculated, and $t$ is time. The system (1) should be subjected to boundary and initial conditions, which predefine the nodal displacements and velocities at time $t = 0$.

The most computationally efficient way for solving the equation (1) is the use of the explicit integration rule together with diagonal lumped element mass matrices. The explicit central difference integration operator used can be written in the following form:

$$\mathbf{U}^{(i+\frac{1}{2})} = \mathbf{U}^{(i-\frac{1}{2})} + \frac{\Delta t^{(i+1)} + \Delta t^{(i)}}{2} \mathbf{U}^{(i)}, \quad (2)$$

$$\mathbf{U}^{(i+1)} = \mathbf{U}^{(i)} + \Delta t^{(i+1)} \dot{\mathbf{U}}^{(i+\frac{1}{2})},$$

where the superscript $i$ refers to the increment number and $(i-\frac{1}{2})$ and $(i+\frac{1}{2})$ refer to midincrement values. The explicit procedure requires no iterations and no tangent stiffness matrix, because the accelerations at the beginning of each increment can be calculated quite simply by the inversion of the lumped mass matrix diagonalized in advance as:

$$\mathbf{\ddot{U}}^{(i)} = \mathbf{M}^{-1} \cdot \left(\mathbf{F}^{(i)} - \mathbf{I}^{(i)}\right), \quad (3)$$

where $\mathbf{I}$ is the vector of internal forces. The explicit procedure integrates the equation (1) through time by using many small time increments. The time increment used in an analysis must be smaller than the stability limit of the central-difference operator. An approximation to the stability limit is defined by the smallest transit time of a dilatational wave across any of the elements in the mesh as the following: $l_e/c_d$, where $l_e$ is the characteristic element dimension and $c_d$ is dilatational wave speed of the material.

The transient dynamic analysis of sandwich plates containing impact
damage is carried out with ABAQUS/Explicit [12] using the explicit integration rule, and where the contact-impact conditions for normal and tangential interactions of surfaces coming into contact can be modeled. The contactable parts of the vibrating sandwich plate are simulated by using their surface-to-surface discretization with finite kinematic contact assumptions. The hard contact model, obeying strong non-penetration conditions is accepted. To resolve the normal contact-impact conditions imposed, the penalty algorithm that does not increase the number of governing equations is used. For the sake of reducing the computational cost and because the sliding in the contacting surfaces is negligibly small for being studied the dynamic behavior, the tangential contact conditions are adopted as frictionless.

Assuming a pure elastic material behavior we will introduce no energy dissipation into the FE model that results in the physically unreal case when the contactable surfaces are bouncing back immediately after impact always during vibrations. In order to improve the model proposed but to not annihilate transient responses immediately, a small amount of artificial numerical damping is introduced in the form of bulk viscosity to control high frequency oscillations. In this paper, the presented results were obtained by using the damping ratio of 1% of critical for both linear and quadratic bulk viscosities.

6.3. Numerical Results and Discussions

The sandwich plate analyzed is a simply supported rectangular plate of a 180 mm by 270 mm consisting of 50 mm-thick PVC H85 foam core and 2.4 mm-thick GFRP face sheets, material properties of which as well as the dimensions of the impacted site are given in Table 1. An impulse concentrate load is applied at the center of the undamaged face sheet of the plate. The impulse is defined by a step function. The duration of the applied load is 100 times smaller than the time step of the analysis equal to 10 ms. Fig. 3 presents the deformed forms of the plates during the transient motion at the different discrete times for first 2 ms. It can be clearly seen the intermittent contact of the detached surfaces in the vibrating sandwich plate. Thereby, it is plausible to suggest the influence of this local behavior on the global dynamic response of the sandwich plate.

<table>
<thead>
<tr>
<th>Table 1. Parameters for the sandwich plate.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material properties: PVC H 85 - $E_c = 135$, MPa $G_c = 45$, MPa $\rho_c = 100$, kgm$^{-3}$; GFRP - $E_{11} = E_{33} = 16500$, MPa $E_{22} = 3800$, MPa $G_{12} = G_{23} = 1800$, MPa $G_{13} = 6600$, MPa $\rho_f = 1650$, kgm$^{-3}$</td>
</tr>
<tr>
<td>Impact zone dimensions: $R_{dent} = R_{cr} = 39.3$, mm $\delta_{dent} = 2.4$, mm $\delta_r = 15$, mm $\delta_{cr} = 5$, mm</td>
</tr>
<tr>
<td>t=0.1ms</td>
</tr>
</tbody>
</table>
Fig. 3. Deformed shapes of impact damaged sandwich plate

The same sandwich plate was analyzed with and without contact conditions at the impacted region in order to evaluate the effect of intermittent contact-impact during the transient oscillations. Besides, the transient motion of the intact sandwich plate of the same size and constituent materials was also considered. The variation of the transverse displacement, velocity, acceleration and the longitudinal logarithmic strain, calculated at the center point of impacted face sheet with a time are shown in Fig. 4. As one can see that the neglecting of contact leads to incorrect results which mainly overestimated the amplitude of the dynamic responses of all parameters presented. Taking into account the
contact model for the imperfect core-to-face sheet interface dampens the magnitudes of the displacement, velocity, acceleration and strain compared to the model without contact.

Fig. 4. Time history of the central point of the impacted face sheet: a) displacement, b) velocity, c) acceleration, and d) longitudinal logarithmic strain.
This is because the contact model is of importance to prevent the interacting fragments from overlapping each other and on the other hand to model their contact-impact behavior that is necessary for properly presentation of the global dynamic response. Moreover, it also follows form Fig. 4 that the transient dynamic responses for intact sandwich plate and plate with core-to-face sheet debonding as a result impact damage are quite different. These changes in dynamic characteristics may be applied to the vibration-based non-destructive diagnosing of impact-induced damage.

6.4. Conclusions

The results, obtained in the paper demonstrate that the local interaction, detached fragments within the sandwich plate is very important to properly describe the transient dynamic behavior of sandwich plate with impact-induced damage. The nonlinear analysis taking into account contact conditions is required in this case. The neglect of contact in the transient dynamic behavior will overestimate the dynamic response. Moreover, it one can suggest that the contribution of contact will increase with increasing the size of the impact region.

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7. Numerical investigation of laminated glass impact

7.1. Introduction

The laminated glass became very popular as safety glass, because the very elastic interlayer of Poly-Vinyl Butyral (PVB) withstands large straining and keeps the integrity of the laminated glass after the shattering of the glass layers which are bonded by the PVB-interlayer. The laminated glass is applied in architectural glazing of buildings. In the case of hurricane, earthquake, tornado and some other disasters, the broken windows of such buildings have no falling sharp pieces of glass jeopardizing the live of people. The other application of the laminated glass is in automotive industry where it is mandatory the windshield of the cars to be made by laminated glass. In traffic accidents, the laminated glass prevents the penetration of the passengers outside of the car and of the pedestrians or cyclists inside of the car.

In order to improve the laminated glass, we should know the failure mechanism in the case of typical loading of laminated glass applications. Belis et al. [1] have experimentally investigated the failure mechanism under static loading for the architectural application of the laminated glass. Biolzi et al. [2] added a numerical investigation by Finite Element (FE) method to similar investigation of the failure mechanism of laminated glass under bending loading. The typical catastrophic event for failure of laminated glass, however, is the low velocity impact of a small projectile like the roof debris for the architectural application or of a human head for the automotive application.

FE method is powerful tool for investigation of the progressive failure by numerical experiments. If a proper material model is developed, FE analysis and simulations could give a great insight of the catastrophic events like structure failure under impact. Zhao et al. [3] have developed a constitutive model of glass based on continuum damage mechanics and they have investigated the progressive failure of laminated glass under low velocity impact by 2-D FE model in ABAQUS™ software.

A 3-D FE model of laminated glass plate has a lot of Degrees of Freedom (DoF) and therefore it requires powerful computers and long time for calculations. Du Bois et al. [4] used shell and membrane finite elements in order to reduce the number of DoFs in a 3-D modeling of laminated glass for crush simulations. The glass layers are modeled with strain failure of the material and without energy dissipation. Some mesh dependence can be noticed in the fracture pattern. The irregular mesh can improve the model and the typical radial

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and circumferential cracks could appear in the FE simulations [5]. Extended FE method (X-FEM) became a very useful for crack propagation simulations and crack path investigations. Xu et al. [6] investigated the path of crack propagation in a rectangular laminated glass plate under impact but they consider only one crack in a quasi-static loading because the application of the method and its implementation in the ABAQUS™ software is still quite restricted.

The aim of this work is to develop a computational model of laminated glass in FE software in order to simulate low velocity impact and to investigate the progressive failure of laminated glass and its mechanism.

7.2. FE model

Full circle of laminated glass plate with diameter of 480 mm has been modeled by 3-D hexahedral finite elements with reduced integration. The thickness of glass layers is 2 mm while the thickness of the PVB-interlayer is 0.76 mm. Four plies of elements are used to model the glass layers and only one ply for the PVB-interlayer. The projectile has a diameter of 72 mm and it has been modeled as a half of rigid body sphere by shell elements. The FE model is presented in Fig. 1. The lower peripheral edge of the plate is simply supported. The initial velocity of the projectile is 6.67 m/s and its mass is 4.5 kg.

![Fig. 1. Finite element model](image_url)

The elastic properties of the glass are determined by the Young’s modulus, \( E = 72 \text{ GPa} \), and the Poisson’s ratio, \( \nu = 0.25 \). The mass density of the glass is 2500 kg/m\(^3\). The PVB material is modeled as a hyper-elastic material with Poisson’s ratio 0.49 and the tensile test data for the nonlinearity are given in Table 1. The mass density of PVB-material is assumed to be 1100 kg/m\(^3\).

<table>
<thead>
<tr>
<th>Strain, (\varepsilon)</th>
<th>0.00</th>
<th>0.50</th>
<th>1.00</th>
<th>1.37</th>
<th>1.62</th>
<th>2.00</th>
<th>2.13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress, MPa</td>
<td>0</td>
<td>4</td>
<td>15</td>
<td>30</td>
<td>45</td>
<td>70</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 1. Nonlinear stress-strain data for the PVB-material.
7.3. Smeared cracking model for brittle materials

The X-FEM is the best method maybe representing the discontinuity of cracks in a solid medium. Its recent implementation in ABAQUS™ software [7] is still not so stable in order to represent and to follow the development of multiple cracks that can appear in impact fracturing of naturally brittle material like glass. The method is implemented only in implicit time integration FE software (ABAQUS/Standard), which has limited capability to represent impact-contact dynamics. The smeared crack models with degradation of the elastic properties of the material are alternative, which can give good results if a local damage model using a characteristic length as regularization against the mesh dependence is applied.

The brittle cracking model suitable for concrete and some other brittle materials is used for the glass material in an explicit time integration scheme of FE method. The model initiates a crack using Rankin’s criterion, i.e. when the maximum principle stress, $\sigma_1$, exceeds the limit stress, $\sigma_{\text{lim}} = 23 \text{ MPa}$, ($\sigma_1 > \sigma_{\text{lim}}$). The direction of the maximum principle stress, $\mathbf{n}$, at the time (or the time step) of the initiation of the crack is memorized and fixed as a normal of the crack. The elastic modulus in direction of crack normal, $E_n$, is degraded (material is no longer isotropic) by a damage variable which evolution is linear with respect to crack opening displacement, $u_{cr}$, calculated as

$$u_{cr} = \varepsilon_n L_c,$$

where $L_c$ is a characteristic length of the finite element and $\varepsilon_n$ is the strain in the normal direction of the crack. The evolution of the damage variable is determined by the strain energy released rate [7], $G_f$, which is assumed to be $G_f = 10 \text{ N/m}$.

The brittle cracking model has an optional shear retention model which degrades the shear modulus in the crack plane, $G_{cr}$:

$$G_{cr} = G_0 \left( 1 - \frac{\varepsilon_n}{\varepsilon_{\text{lim}}} \right)^p,$$

where $G_0$ is the initial shear modulus, while $p$ and $\varepsilon_{\text{lim}}$ are material constant which we assumed to be: $p = 1$, $\varepsilon_{\text{lim}} = 0.00517$. When the material is fully degraded in the plane of the crack, the finite element is deleted from the database of the FE model [7]. This is a way to reveal the cracks developed in the model.

The element deletion is not the proper way in dynamic cracking simulations, because it is a mesh dependent and should be combined with adaptive mesh refinement in order to avoid great lost of mass. This is why we decided to apply another software – LS-DYNA®, with very similar smeared
cracking brittle material model but without element deletion [8]. The difference between the damage models is very small. The ABAQUS™ model has three damage variables and the opportunity to develop cracks on three orthogonal planes after the initiation of the first crack and the fixture of its orientation [7], while the LS-DYNA® model has one damage variable and the opportunity to show it as a history variable and its distribution in a contour plot [8]. The damage evolution law is exponential in LS-DYNA® model for both the elastic modulus degradation and the coupled shear modulus degradation. The degradation of material constants is up to 2% of their initial values and a simple Perzyna regularization method is implemented as viscous behavior for stability in LS-DYNA® model.

7.4. Results and discussion

The analysis of failure simulations of laminated glass shows that the radial cracks are developed in non-impacted layer and on the surfaces of non-impacted sides of the layers first then the circumferential cracks are developed on the surfaces of the impacted sides of the layers and in the impacted layer they appear earlier (see pictures of ABAQUS™ simulation in Table 2). The circumferential cracks could be arrested while this is more difficult to happen with the radial cracks. The simulation of LS-DYNA® software with its brittle damage model shows the same pattern of damages which can be seen in the pictures of Table 3.

The crack pattern can be explained by the flexural curvature of the laminated glass plate during the impact and the 2-D stress state on the different surfaces of the different glass layers of the laminated glass plate at different places. Illustration is given in Fig. 2.

First of all, the laminated glass in bending has a stress distribution like the diagrams of stress in Fig. 2a. The resistance of the interlayer in shear has its contribution to the bending moments, $M_1$, so the total bending moment, $M$, is the sum:

$$ M = M_1 + M_1 + M_2 $$

where $M_1$ causes compression in one of the glass layers and tension in the other one.

The hoop stress is always tensile and it is greater on outer surfaces with respect to the plate center (Fig. 2b). The hoop stress causes radial cracks while the radial stress causes circumferential cracks. Because the hoop stress is always tensile, the radial cracks are not restricted in their development and propagation. The radial stress is different on the different surfaces. It is tensile on some of them and compressive on the surfaces of their opposite layer sides (Fig. 2b). The propagation of the circumferential cracks through the thickness of the glass layers could be restricted then in dependence on the dynamics of the crack propagation and the impact.
Fig. 2. The stress state of laminated glass layers in bending and impact deflection.

Table 2. Successive pictures of glass-layer cracking in ABAQUS™ simulation.

<table>
<thead>
<tr>
<th>Time, (ms)</th>
<th>View of non-impacted layer from non-impacted side</th>
<th>View of non-impacted layer from impacted side</th>
<th>View of impacted layer from non-impacted side</th>
<th>View of impacted layer from impacted side</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td><img src="image1.png" alt="View of non-impacted layer from non-impacted side" /></td>
<td><img src="image2.png" alt="View of non-impacted layer from impacted side" /></td>
<td><img src="image3.png" alt="View of impacted layer from non-impacted side" /></td>
<td><img src="image4.png" alt="View of impacted layer from impacted side" /></td>
</tr>
<tr>
<td>4</td>
<td><img src="image5.png" alt="View of non-impacted layer from non-impacted side" /></td>
<td><img src="image6.png" alt="View of non-impacted layer from impacted side" /></td>
<td><img src="image7.png" alt="View of impacted layer from non-impacted side" /></td>
<td><img src="image8.png" alt="View of impacted layer from impacted side" /></td>
</tr>
<tr>
<td>6</td>
<td><img src="image9.png" alt="View of non-impacted layer from non-impacted side" /></td>
<td><img src="image10.png" alt="View of non-impacted layer from impacted side" /></td>
<td><img src="image11.png" alt="View of impacted layer from non-impacted side" /></td>
<td><img src="image12.png" alt="View of impacted layer from impacted side" /></td>
</tr>
<tr>
<td>8</td>
<td><img src="image13.png" alt="View of non-impacted layer from non-impacted side" /></td>
<td><img src="image14.png" alt="View of non-impacted layer from impacted side" /></td>
<td><img src="image15.png" alt="View of impacted layer from non-impacted side" /></td>
<td><img src="image16.png" alt="View of impacted layer from impacted side" /></td>
</tr>
</tbody>
</table>
Table 3. Damage variable contour plot of glass-layer cracking in LS-DYNA® simulation.

<table>
<thead>
<tr>
<th>Time, (ms)</th>
<th>View of non-impacted layer from non-impacted side</th>
<th>View of non-impacted layer from impacted side</th>
<th>View of impacted layer from non-impacted side</th>
<th>View of impacted layer from impacted side</th>
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<tr>
<td>4</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

7.5. Conclusions

The cracking of laminated glass under impact is successfully simulated by FE method using smeared crack damage models. The FE analysis reveals the fracture mechanism of laminated glass. The radial cracks emanate from non-impacted sides of the glass layers could propagate through the whole thickness of the layers. They have higher density in the non-impacted layer and dominate the failure. The circumferential cracks emanate from the impacted sides of the glass layers and they are more pronounced in the impacted glass layer. The circumferential cracks even could not propagate through the whole thickness of the layers.

Acknowledgement

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Jacek Domińczuk¹, Jakub Szabelski²

8. Surface layer energy state and its influence on adhesive strength

8.1. Introduction

There is a growing tendency among modern technological solutions to apply various substances on the materials surface in order to improve their mechanical or antircorrosive properties, as well as to perform technological operations on the surface with the aim of altering the state of the surface layer [1]. It is dictated by high cost-effectiveness of such procedures with relation to significant enhancement of functional qualities of the product. The technological procedure of adhesive joining machine parts, both in assembly and regeneration processes, is developing at a high rate and is directly connected with the processes occurring at the material’s surface layer. Acquiring knowledge of adhesive processes associated with constitutive properties of the surface layer would significantly improve the practical application of gluing technology [2].

The research in the field indicates that the strength of an adhesive joint depends on the surface layer energy properties of the material undergoing the technological process. However, the state of knowledge of the dependencies between surface layer energy and the state of the layer itself is incomplete [3]. Shaping adhesive strength, i.e. the strength on the boundary of joined materials, is influenced by various factors, e.g. geometrical structure of the surface, its chemical composition, the morphology of the produced conversion coating, physical lattice defects of the surface, surface energy state in general along with the properties of the applied substance (e.g. glue). Due to the fact that the state of the coated samples surface is frequently disturbed, the contact surface between the adherend and the joint (e.g. adhesive joint) is many a time the most sensitive area of the joint. The aforementioned conditions contribute to the manifold character of adhesion phenomena [4].

8.2. Sources of surface energy

What is considered as the surface of a body is the phase boundary, the point of an discrete change of one phase’s properties to the properties of the other. On the condition that the body is not in vacuum, this is the surface of the body which is the interfacial surface. Possible phase boundaries are as follows: liquid-gas, liquid-liquid, liquid-solid, solid-gas, solid-solid.

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Surface layer is the layer of a material limited by the specific (external) surface of the object (product), including this surface and a portion of the material within a certain distance from the specific surface, which is frequently of different physical and even chemical properties compared to the properties of the material deep within the object [5].

Boundary surfaces occur when the structural elements of the body (atoms, ions, molecules) are interlinked by significant cohesion forces. Should the cohesion forces be low – the dispersion of one substance in another will take place [6].

In the case of placing a solid in gas or liquid, the boundary surface becomes the interface. Similarly to the previously mentioned case of vacuum, molecules constituting the surface are within the body. On the external side of the interphase the molecules of the solid are surrounded by molecules of another phase, the reaction with which considers different forces than the reaction with the elements of their own phase (Fig. 1).

![Fig. 1. Forces acting on molecules inside the body and at its surface [6].](image)

For liquids and gases the forces in question are considerably lower than those acting from within own phase. As a consequence, certain forces of surface molecules of a solid are uncompensated, therefore the surface is higher in energy than the inside of the solid. Naturally, both internal and surface molecules interact with molecules in contact, nevertheless, the bigger the distance of molecules from the surface, the weaker action on the molecules at the surface (Fig. 2.).
Solids surface atoms are extremely limited in terms of movement freedom. Cohesive energy density depends, among others, on other surrounding atoms. With the decrease of the amount of these around the atom, the degree of forces density is reduced and surface energy increased (Fig. 3.)

Surface energy is what may be considered as an indicator of non-equilibrium of cohesive forces between molecules inside and at the surface of the body. It constitutes an inseparable characteristic of a surface, additionally, its value and distribution is determined by the type of chemical bonds, ergo, the type of body. It mainly distinguishes solids, regardless of the degree of structural ordering [5].

Surface energy is the difference between the total energy of all surface atoms or molecules and their potential energy, were they situated inside the body. Surface energy may be considered as a quantity of work needed to transfer atoms or molecules from within the body to its surface. In the case of critical state (i.e. a two-phase, one-component, system where physical properties of both phases in equilibrium state become identical, for critical pressure and
temperature), surface energy equals zero as a result of lack of phase difference, therefore the disappearance of the surface [7].

Surface energy should not be understood as the energy of molecules and atoms constituting the surface. Such implication is false on account of the fact that the surface molecules energy increases with the increase of temperature while surface energy decreases and for critical temperature equals to zero [8].

8.3. Energy properties of the surface

8.3.1. Energy balance

Each body possesses a certain amount of energy. If kinetic (connected with movement) and potential (connected with orientation) energies are disregarded, what remains is the energy of a body related to its structure, which may be broken down into internal and surface energy.

Internal energy is the total energy stored within the body. The types of energy which contribute to the total quantity of energy are the following: translational and rotary motion energy, atoms intramolecular vibrational energy, electronic states and nuclear energy, together with all other forms of intrinsic energy of a body. There has been no method developed which would enable to measure the absolute value of intrinsic energy; only its changes are known, which provide the base for calculating various thermodynamic functions changes.

Based on the aforementioned theories, the following formula for calculating the total energy of a body may be derived:

$$E = c_m \cdot m + e_p \cdot A$$  \hspace{5cm} (1)

Resulting from dividing the equation (1) by the mass of the body, the following formula for intrinsic energy per mass unit is developed [7]:

$$\frac{E}{m} = e_m + e_p \cdot \frac{A}{m}$$  \hspace{5cm} (2)

The quotient $\frac{A}{m}$ considers the surface per mass unit and is referred to as specific surface area. In the case of non-complicated surface bodies, the values of the $\frac{A}{m}$ expression are negligible, therefore the second term of an equation (2) can be disregarded.

8.3.2 The possibilities of shaping the surface energy state

As it has been already mentioned, the surface energetic state is extremely complex and depends on a number of factors, some of which are interdependent, which results in an even more complicated process of forecasting the effects of surface activation operations.
The specificity of many technological processes requires achieving a specified surface energetic state, therefore, e.g. in painting process the aim is to obtain maximum surface energy, which results in increased adhesive activity of the surface and contributes to forming a more durable layer. On the other hand, surface treatment process in the case of slide bearings is focused on providing a surface resistant to adhesive corrosion (low surface energy value), at the same time fulfilling the condition of proper lubrication. In order to meet such requirements the knowledge of factors affecting surface phenomena and their values is essential. Such knowledge would enable to plan the technological process properly, purpose-wise.

In the macroscale, the surface state, its character, profile, surface stresses, hence surface energy and reactivity are determined by the following factors:

- surface treatment history (machining – cutting, turning etc, heat treatment – hardening, tempering, annealing etc, abrasive machining – grinding, superfinish, honing, polishing etc, chemical treatment, thermochemical treatment – nitriding, carburising etc, electrolytic treatment – chroming, nickelising etc, electromachining),
- operating factors
- atmospheric factors

The aforementioned factors influence the surface state. Surface energy together with reactivity and the resulting adsorption or chemisorption capability are connected with the character of surface, its profile, defects and stresses.

Basing on research results [7], as well as on conclusions from the profile of surface energy can be generally presented superficial energy by the function:

\[ E_s = F(f , R_z, ch, T, i, \sigma_{in}, H, UTS, li) \]  

where:

- \( f \) - filler type;
- \( R_z \) - roughness parameter;
- \( ch \) - chemical factors;
- \( T \) - temperature;
- \( i \) - impurities in surface layer;
- \( \sigma_{in} \) - internal stresses;
- \( H \) - hardness;
- \( UTS \) - ultimate tensile strength;
- \( li \) - lattice imperfection.

Depending on the type of filler used, different ratio of force distribution in surface layer can be achieved, which is connected with the amount of energy and uniformity of its distribution. It is particularly observable in plastics [9].

The degree of surface developed radically influences energetic properties of surface layer, which was proved in experimental research – the examination of adhesion work for steel 1.4541 after processing with various granularity abrasive tools. The measurements method was presented in paper [10]. The results show that for this particular steel it is better to process it using abrasive tool of smaller grain (Fig.4).
The research results did not reveal essential significant difference between the work of adhesion after processing with P320 or P500 granularity abrasive tools, which seem to indicate larger influence of the mechanical surface development than of the structure and dynamism of creating the physically adsorptive layer.

In order to change the surface layer energy the surfaces of joined materials can be chemically or physically activated. Such an activation can be achieved by formatting specific stereometric characteristics of the surface layer, or by introducing functionally active groups through chemical reactions. Different surface layer energy states are achieved by applying various types of substances to activate the surface layer. The chemical pickling widely used for preparation of surface layer of material to be painted or glued is an example of such processing. The work of adhesion research results for steel 1.4541 after chemical pickling in bath solution of three parts by weight of $\text{H}_2\text{SO}_4$, two parts of $\text{Na}_2\text{Cr}_2\text{O}_7$ and seven of $\text{H}_2\text{O}$ were introduced in Fig. 5.

Basing on earlier mentioned theorem [7] that surface layer energy in critical state equals zero, and on the basis of the thermodynamical function describing the dependence between surface tension and surface layer energy it can be concluded that the increase of temperature (near critical value) leads to decrease of surface energy:

$$\sigma = E_p + T \frac{d\sigma}{dT}$$

The environment where top surface layer is formed, as well as body’s storage conditions, especially humidity and presence of organic and inorganic air pollution can influence surface layer energy. Regardless of a processing operation and a processed material, molecules at the surface show significant chemical activity which in turn affects the surface influence on the surrounding
environment: gas, liquid, solid body. This results in adsorption of external substances which can finally cause lowering the surface energy of the surface layer. In normal conditions of storage or exploitation surfaces of metals are usually covered with the layer of oxides, adsorbed organic compounds and gases.

Fig.5. The influence of chemical pickling on the work of adhesion for 1.4541 steel - H₂O system, 1- raw state steel, 2-steel after 10 min. pickling, water rinsing and 30 min. drying in ambient temperature [10]

The increase of internal stresses in the surface layer simultaneously causes increase of surface energy, under the condition that the factors which lead to this increase do not bring about significant deterioration of other physical or stereometric characteristics of the surface layer.

The factor facilitating the process of increasing the surface energy is the increase of surface layer hardness. It is connected with higher force desaturation in the surface layer, which becomes more energetically active. The tests of adhesion work were conducted on samples of 6 mm thick, various hardness 1.0503 steel. Test pieces were subjected to the following thermal processing operations: quenching and tempering, hardening, annealing. The studied material, after aforementioned processing, manifested the following hardnesses, respectively: 20 HRC, 50 HRC, 20 HRC. The test results are gathered in Fig. 6. The results concern measurement of the adhesion work for specimens in raw steel state, specimens after processing with abrasive tool and specimens after processing with abrasive tool and degreasing, after every single step of heat treatment.
The significant increase of adhesive properties of steel was noticed after heat treatment, which results from high energetic activity of the surface layer. For raw steel, such high adhesion work is a result of creation of highly energetic layer of oxides. What can be noticed is the decrease of adhesive properties after removing through abrasive processing the thin layer of oxides. Moreover, the relative adhesive work is comparatively high compared to steel prior heat treatment. Degreasing after the abrasive processing results in the increase of adhesion work compared to abrasive processing itself; it is connected with the removal of impurities from the surface of the sample. A particularly interesting observation is the comparison of adhesive properties of steel after annealing. What can be observed is the stability of work of adhesion which indicates equilibrium in the surface layer energy after each of the operations.

The material type significantly influences the surface energy. This is connected with crystal, mesh structure, or even molecular and atomic. Considering crystals on metal surface, it is observed that with their growth, the surface energy increases likewise. It is a result of larger desaturation of molecular forces caused by considerable intermolecular distances. It is also known, that the presence of atoms, such as the oxygen, causes the decrease in energetic characteristics of surfaces as a result of creating thin conversional layers.

The structure defects, such as: cracks, microshrinkages, wormholes, gaps, crevices influence considerably the energetic state of surface. The area of a higher energetic activity is created between those defects as a result of the particles with uncompensated bonds quantity increase. The surface layer state including all the aforementioned structure defects is presented in Fig. 7.
8.4. The analysis of the influence of energetic properties of the surface layer on the joint strength

The analysis of adhesion work after various methods of materials’ surface layer treatment indicates the need to search for correlation between energetic properties and the strength of joint [3, 7, 10, 11, 12].

The experimental tests were conducted using a specially constructed test stand [13].

The results of comparative research for 1.0426 carbon steel are introduced in Fig. 8.

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**Fig. 7.** A set of surface layer of a solid structure defects on the 3-layer model of a surface layer: t - surface layer thickness; s - surface layer structure; h - hardening in the central zone; \( \sigma \) - internal stresses in the surface layer; 1 - microcracks; 2 - crevice; 3 - microshrinkage; 4 - wormhole; 5 - gap; 6 - inclusion

**Fig. 8.** The comparison of an adhesive joint strength a) for steel 1.0426 with adhesion work, b): 1 - after the P320 abrasive tool processing, 2 - after the P320 abrasive tool processing and degreasing with the Loctite 7061, 3 - after the P320 abrasive tool processing and water rinsing [14].
The observed increase of adhesion work for the steel after processing with P320 abrasive tool and rinsing with water is not reflected in joint strength, which decreases. No relation between the adhesive work for steel after using variable granularity abrasive tools and the relative strength of a joint after P320 abrasive tool processing was observed.

Comparing the joint strength with surface energy determined using the Owens-Wendt’s method led to interesting results. The total free energy (also called the surface energy) is known to consist of dispersion and polar components. Such division is conventional because the adhesion theory is still being developed. The second measuring liquid, significantly different than water in terms of energetic properties – methylene iodide – CH$_2$J$_2$ was used in the experiment. By measuring the contact angle of the two liquids, after some transformations known from the thermodynamics of wetting, it is possible to determine the relation to calculate surface free energy. The results of calculations after the measurements are gathered in Table 1.

Table 1. The component values of free surface energy for 1.0426 steel

<table>
<thead>
<tr>
<th>Surface condition</th>
<th>Surface free energy [mJ/m$^2$]</th>
<th>Non-polar component [mJ/m$^2$]</th>
<th>Polar component [mJ/m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P320</td>
<td>66,28</td>
<td>65,76</td>
<td>0,52</td>
</tr>
<tr>
<td>P320 degreased</td>
<td>67,94</td>
<td>65,32</td>
<td>2,63</td>
</tr>
<tr>
<td>P320 rinsed</td>
<td>65,54</td>
<td>56,31</td>
<td>9,23</td>
</tr>
</tbody>
</table>

By comparing individual components of surface free energy, the relation between non-polar component and joint strength can be observed – Fig. 9. That, however, is insufficient to unequivocally define the type of the relationship, as more analyses including other methods of determining surface free energy e.g. the Van Oss-Good’s method [15] are required.

Fig. 9. The comparison of adhesive joint strength with a) a dispersive component of free energy for steel 1.0426 b): 1 - after processing with P320 abrasive tool, 2 - after processing with P320 abrasive tool and degreasing with Loctite 7061, 3 - after processing with P320 abrasive tool and water rinsing.
8.5. Summary

The conducted tests and analyses seem to ground the conviction that surface energy values is heavily influenced by surface treatment processes, which form the geometry of the surface. Appropriate data concerning the energetic dependence of a given material surface layer on the stereometric features of the surface allows to plan machining and abrasive machining processes with a view to obtain an optimum energetic state of the surface layer. It consequently contributes significantly to reduce machining costs and increases the product lifetime. The function describing the surface energy value is complex not only due to the number of factors influencing the function’s value, but also owing to the temporal instability of its characteristics. In ought to be mentioned that the intensity of changes of physical or chemical features in particular areas of the surface layer obtained in the technological or operation processes is non-uniform.

The tests conducted on a sample of 1.0426 steel indicate that both abrasive machining and degreasing improve adhesive properties of the sample’s surface layer. The observed increase in the work of adhesion after water rinsing is associated with oxidation processes activation, which, however, does not guarantee a better-quality adhesive joint in the case of steel, since the products of corrosion are loosely connected with the base material.

It appears that investigating into dependencies between the dispersive surface energy and adhesive joint strength might prove interesting, inasmuch as it could lead to drawing dependencies enabling a more accurate description of adhesive properties of carbon steel. The tests and analyses of the surface layer state presented in works [10, 14, 16] indicate that it is impossible to determine direct dependence between the work of adhesion values and joint strength. Therefore, the wetting angle alone could be insufficient an indicator of surface layer preparation for gluing and sealing. This information is of significant practical importance as the thermodynamic measure of adhesive properties cannot be always applied into practice.

All the presented material demonstrates the importance of surface development and chemical purity on joint strength, which in turn manifests the relation between the strength of adhesive joints and the energetic state of the surface layer.
Bibliography

Project: Centre Of Excellence For Modern Composites Applied In Aerospace And Surface Transport Infrastructure

Project: CENTRE OF EXCELLENCE FOR MODERN COMPOSITES APPLIED IN AEROSPACE AND SURFACE TRANSPORT INFRASTRUCTURE

Acronym: CEMCAST FP7-245479

Coordinator: Tomasz Sadowski, Ph.D., D.Sc., Prof.
Administrator: Jolanta Sadowska, MSc
Lublin University of Technology

Total cost: 2 560 000 EURO

Period: 1 April 2010 – 31 March 2013

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Scientific goal
1. modelling of modern composite materials with application of multi-scale method (nano-, micro-, meso-, macro-) and application of newly formulated concepts to solution of engineering problems in aerospace and surface transport infrastructure—research under the supervision of prof. Tomasz Sadowski
2. modelling and control of dynamics of structures made of composites with embedded active elements taking into account geometrical and material nonlinearities, active and passive vibration, modeling of machining of composites — research under the supervision of prof. Jerzy Warmiński

Work Plan

- WP 1: Increasing of the research capacity through twinning with the leading centers
- WP 2: Expanding of the scientific expertise by recruitment of experienced researchers
- WP 3: Organisation of scientific events
- WP 4: Participation of the CMCM staff in international events
- WP 5: Management
- WP 6: Upgrading research equipment
- WP 7: Cooperation with SMEs and industry
- WP 6: Dissemination and promotional activities

Lublin University of Technology, Poland Faculty of Civil Engineering and Architecture
Planned activities:

- **twinning collaboration** with 11 foreign universities (visits of LUT staff – 68 months, visits to LUT – 57 months
- **recruitment** of 5 experienced foreign researchers
- **organisation** of 3 workshops, 3 mini-symposia at international conferences (France, Italy, China) and course at International Centre for Mechanical Sciences (Udine, Italy)
- **participation** in 25 international conferences
- **purchase** of research equipment - 770 000 Euro

Lublin University of Technology, Poland  Faculty of Civil Engineering and Architecture

- Task 1.1 Twinning with the **Martin Luther University, Germany** – Prof. Holm Altenbach
  Topic: Modelling of thermomechanical behaviour of composites
- Task 1.2 Twinning with the **Aalborg University, Denmark** – Prof. Ryszard Pyrz
  Topic: Structural characterisation of polymer matrix composites
- Task 1.3 Twinning with the **University of Glasgow, UK** – Prof. Matthew Cartmel
  Topic: Nonlinear dynamics and vibrations of composite structures with active elements
- Task 1.4 Twinning with **University of Aberdeen, UK** – Prof. Marian Wiercigroch
  Topic: Experimental and numerical analysis of structures with geometrical and material nonlinearities
- Task 1.5 Twinning with the **University Roma “La Sapienza” , Italy** – Prof. Giuseppe Rega
  Topic: Modelling and nonlinear vibrations of flexible and composite structures
- Task 1.6 Twinning with the **Polytechnic University Marche, Italy** – Prof. Stefano Lenci
  Topic: Modelling of intelligent composite materials and mechanical systems with application of nonlinear dynamics
• Task 1.7 Twinning with the University of Stuttgart, Germany – Prof. Siegfried Schmieder
  Topic: Multiscale modelling and experimental analysis of ceramic matrix composites (CMC)
• Task 1.8 Twinning with the National Technical University of Athens, Greece – Prof. George Papadopoulos
  Topic: Testing of polymer matrix composites. Multiscale modelling of damage and fracture processes
• Task 1.9 Twinning with the University of Porto, Portugal – Prof. Pedro Ribeiro
  Topic: Modelling and experimental testing of structures made of modern composite materials
• Task 1.10 Twinning with the Politehnica University of Timisoara, Romania – Prof. Liviu Marsavina
• Task 1.11 Twinning with the University of Rousse, Bulgaria – Prof. Ivelin Ivanov
  Topic: Impact loading response of modern composite materials applied in aerospace and surface transportation

Recruited researchers:

for 24 months
1. Prof. Vera Petrova (Russia) – „Thermal shock modelling in modern composite materials. Damage and fracture process in functionally graded materials”
2. Assoc. Prof. Mirea Birsan (Romania) – „Layered composite plates and shells subjected to thermal and mechanical loading”
3. Assoc. Prof. Vyacheslav Burlayenko (Ukraine) – „Modeling and experimental investigations of damage and fracture process in the sandwich structures under mechanical loading – cyclic and impact”
4. Prof. Emil Manoach (Bulgaria) – „Nonlinear dynamics and control of flexible structures with active elements”
5. Dr. Fotios Georgiadis (Greece) – „FEM modelling, optimisation and experimental investigations of flexible structures with active elements”
Effects of the project:

- **development** of the full research potential of LUT staff comprising:
  a) modelling of composites,
  b) applications of composites to aerospace and transport infrastructure
  c) modelling and control of dynamics of structures made of composites
- **upgrading** the quality of research carried out at LUT
- **strengthened** international position of the LUT staff by increased research capacity
- **encouragement** of young staff to do research at the international level
- **modernisation** of research equipment
- better **integration** of the LUT staff in the ERA
- deeper **involvement** of the LUT staff in EU projects (FP7)
- closer **co-operation** with the regional industry
- **improved** research capacity for increased contribution to regional economic development
- **Improvement** of research management and organisational skills