



# The Analysis of Influence of Compression Forces on the Strength of MM „Stahl 1018” Composite with the use of SolidWorks Software

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## Abstract

Composite Multimetal Stahl 1018 has been used in the process of preserving worn surfaces of materials operating in extremely difficult conditions. This work presents the results of simulation of the mechanical properties of steel samples in contact with the MM "Stahl 1018" composite. Tests were carried out for various models with one- and two-sided contact sample models with the composite. Theoretical tests were conducted in the "SolidWorks 2019" environment. It was found that the maximum strength of the specimen layer made of MM "Stahl 1018" material, which closely adheres to the surfaces of steel bases on both sides (444 MPa) is higher than that of the material layer in one-sided contact (358 MPa), for specimens with a height of 4.5 mm and at 80 °C. Simulations also revealed a significant increase in the maximum stress in the composite MM "Stahl 1018" for specimens in the so-called free state from 285 MPa to 358 MPa with the increasing temperature from 20 °C to 80 °C, for specimens 4.5 mm high.

**Keywords:** Composite MM Stahl1018, SolidWorks, Computer simulation, Mechanical strength

## 1. Introduction

The Multimetal (MM) "Stahl 1018" composite was designed to regenerate and maintain worn out surfaces of steel, cast iron or other composites and plastics [1-3]. Ever since that material has been successfully used in the process of fixing bridge pillars, railroad and road bridges or canal bridges [4]. MM "Stahl 1018" consists of polymers, a chemically treated epoxy resin, which after curing, shrink only little and have good chemical resistance. The powder-fillers consist of high-quality stainless steel (steel 18-10, EN10088), ceramics and additives to improve the surface tension and chemical resistance. MM "Stahl 1018" is easily applicable, and

thanks to its good forming properties can be evenly distributed on the preserved surface.

Scientific literature does not give much insight into the experimental research on MM "Stahl 1018" and its applicability. Consequently, few publications present the results of this type of analyses [1-9].

The authors of the paper [1] conducted a series of strength tests of the composite at temperatures from 20 to 80°C and on this basis determined the yield strength of the composite. The highest durability of the composite was found at 20°C. In the course of further experiments the hardness and microhardness could be defined, and adhesion (material's ability to adhere to metal surfaces) studied [3]. Besides, impact tests were conducted [2].



It was confirmed in another work [2] that the composite can be used in real conditions on a large device that operates under constant vibration loads and at high temperatures of up to 80°C. Moreover, the material can serve as a kind of shock absorber for a device that prolongs its operation [2].

The author of [5] determined the dependence of the conventional yield strength on such factors as the height and diameter of the specimen. Experimental tests were carried out on an RMDO-20 press with the specimens of height: H=2mm, H=4mm, H=6mm, H=8mm and diameter D=20mm. Experimental data showed that the optimum value of the conventional yield strength corresponded to samples with excess (i.e., samples with partial confinement in the metal base) and a depth of 1mm. The result was a maximum compressive strength of  $\sigma_m=160\text{N/mm}^2$ . However, it should be noted that the empirical relationship of the conventional yield strength obtained by the authors for the samples with excess was approximated ( $\sigma_m=160\text{N/mm}^2$ ), which affects the error in determining the value of the theoretical yield strength. Moreover, it is reduced to the parameter limits within which it was determined.

Compression tests of MM Stahl1018 composite specimens were conducted by Vorona [6] with the use of SolidWorks and Compas software. Author conducted compression simulations at a load of 160MPa, and the results showed that the zone of high stress (about 11MPa) was located at the boundary of the material - the lateral edge of the groove, and also at a distance of 100mm from the edge of the specimen, which is due to the position of the slots in the specimen - shifted inward.

The literature studies confirm the fact that data on the physicochemical, material and mechanical properties of MM composite "Stahl 1018" are limited and incomplete. The results obtained by various authors helped obtain some empirical dependence of the mechanical characteristics of the material on the geometric parameters of the cross sections. Basic information on how the material behaves under dynamic loading conditions has also been obtained [1-9].

## 2. Materials and Methods

When restoring machine and equipment parts with MM composite "Stahl 1018" there are two ways of contact between the composite and the surface to be preserved: one-sided and two-sided contact fig. 1a and b. In practice, the one-sided contact (Figure 1a) is mainly used for maintaining bearings, working surfaces of hydraulic and pneumatic cylinders, shafts, pump rotors, machine guides, etc., whereas its two-sided contact (Figure 1. b) is used for fixing surfaces between two contacting planes [10].

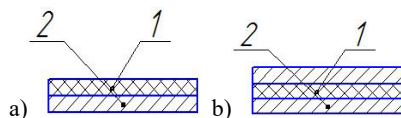


Fig. 1. A schematic of an interface of MM "Stahl 1018" material and the preserved surface: (a) one-sided contact, (b) - two-sided contact, 1 - layer of MM "Stahl 1018"; 2 preserved surface

In the study of mechanical properties of specimens made of MM "Stahl 1018", different variants of composite specimen models were tested, including models with one-sided and two-sided contact:

- 3 cylindrical specimens with two-sided contact of MM "Stahl 1018" (diameter D.= 20mm, height H = 1.5mm, H = 3mm and H = 4.5mm) with two steel cylindrical bases (D = 20mm, height H = 10mm);
- 3 cylindrical specimens with one-sided contact of MM "Stahl 1018" (diameter D = 20 mm, height H = 1.5mm, H = 3mm and H = 4.5mm) with steel cylindrical base (diameter D = 20mm, height H = 10mm)
- 3 cylindrical specimens with a partial casing of MM "Stahl 1018" (diameter D = 20mm, height H = 1.5mm, H = 3mm and H = 4.5mm) in a metal container (diameter D = 20mm, height N = 10mm, penetration depth h = 1mm);
- 3 cylindrical specimens of MM "Stahl 1018" (diameter D = 20mm, height H = 1.5mm, H = 3mm and H = 4.5mm).

The procedure for creating models of test specimens in "SolidWorks" lied in introducing all the mechanical parameters and material properties specified in Tables 1 and 2 [12].

Table 1.

Technical data for MM "Stahl 1018" [11-12]

Compressive strength, $\sigma_m$	N/mm <sup>2</sup>	Max160
Tensile strength, $R_m$	N/mm <sup>2</sup>	76
Flexural strength, $f_m$	N/mm <sup>2</sup>	89
Tensile and shear strength	N/mm <sup>2</sup>	22
Young modulus, E	N/mm <sup>2</sup>	14 000
Linear thermal expansion coefficient, $\Delta t$		$32 \times 10^{-6}$ K
Thermal resistance		- 40°C / +90°C
Chemical resistance		Very good
Resistance to aging and atmospheric conditions		Very good
Working time with the material, t	min	45
Hardening at temperature 5°C, $t_5^{\text{utw}}$	hrs	72
Hardening at 20°C, $t_{20}^{\text{utw}}$	hrs	24
Specific gravity, $\rho$	g/cm <sup>3</sup>	2,4
Viscosity		Soft paste
Storing, $t_{\text{przech}}$	months	12
Packaging, $m_{\text{pacz}}$	kg	1.5+4.5

The specimens in the "free state" were performed of MM "Stahl 1018" using assembly tools (prepared in advance). Next the matrix parts were removed, leaving only two steel bases and a cylindrical specimen made of the tested composite. The friction coefficients between the steel bases and the composite sample were also changed at intervals, setting the friction coefficient at 0.13. Then an assembly consisting of two components was created: the steel base and the composite, along with the contact boundary. In the next step, the steel bases were matched in the same way as the composite specimens with a steel base, with the friction coefficient value ( $\mu = 0.1$ ) [13] determined for the steel abutment and the steel

base. In this way the coefficient of friction of steel against steel in the absence of lubrication could be simulated as in the experiment, the results of which are presented later in the paper. When creating a specimen with one-sided contact in "SolidWorks 2019," it was sufficient to remove the upper steel base and create new interfaces between the steel pad and the composite specimen, setting the friction coefficient  $\mu = 0.13$  [13]. In contrast, the connection between the lower abutment and the steel base remains unchanged. On the other hand, to create a model of specimens partly encapsulated in a metal matrix, the previously created specimen models were used, and then the upper steel base removed from the two-sided model using the edit tool. The previously created circle with a diameter of  $D = 20\text{mm}$  on the upper surface of the lower steel base was cut to a depth of  $h = 1\text{mm}$  (Figure 2).

Table 2. Characteristic of material used for the base Stal C45 PN-EN 10083-2:1999 [13]

Parameter	Symbol	Unit	Amount
Young modulus	E	N/m <sup>2</sup>	$2.04 \times 10^{11}$
Poisson number	$\nu$		0,3
Shear modulus	$\gamma$	N/m <sup>2</sup>	$7.8 \times 10^{11}$
Density	$\rho$	kg/m <sup>3</sup>	7826
Brinell hardness	HBW	HB	170
Yiel point	R <sub>e</sub>	N/mm <sup>2</sup>	245
Tensile strength	R <sub>m</sub>	N/mm <sup>2</sup>	470
Heat expansion coefficient	$\lambda$	1/°C	$1.19 \times 10^{-5}$
Thermal conductivity	k	W/(M×°C)	48
Specific heat	C <sub>w</sub>	J/(kg×°C)	473

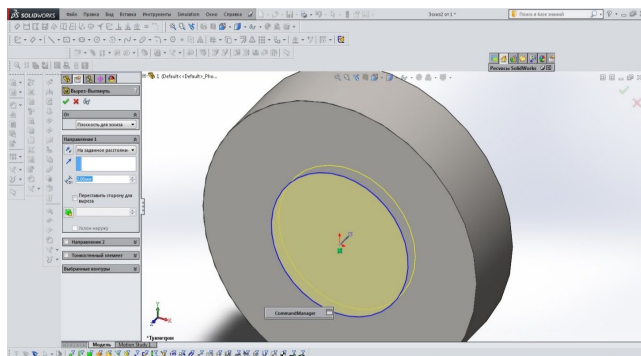


Fig. 2. Formation of samples partly encapsulated in a metal matrix

In the same way, models of specimens partly placed in a metal matrix were made; the heights of the specimens in the part made of MM "Stahl 1018" equaled to: 1mm; 2.5mm; 4mm and 5.5mm, respectively. Also in this case, the sample had to be matched with the metal matrix.

### 3. Determining stresses in specimens made of MM "Stahl 1018" using the program "SolidWorks Simulation 2019"

#### 3.1. Theoretical bases for determining stresses in specimens made of MM "Stahl 1018"

The study of stresses in specimens made of MM "Stahl 1018" was carried out using the "SolidWorks Simulation" package integrated with the "SolidWorks" interface, based on FEM (finite element method) - a numerical method for analyzing deformable body mechanics problems. Finite element analysis is an effective numerical technique for analyzing engineering designs. The method lies in discretizing objects, i.e. dividing the analyzed part into elementary particles and measuring each of them separately [14], to solve "continuum mechanics" equations, provided that the relationships are satisfied in each elementary domain. The effect of loads on the elastic structure causes movement of the material points including displacements relative to each other. The task of the mathematical description of an element is to relate the factors acting at the nodes and to create equations that control the behavior of each element and account for its relationships with other elements:

$$\{F\} = [F_{xg} F_{yg} F_{zg} M_{xj} M_{yj} M_{zj}]^T \quad (1)$$

$$\{\Delta\} = [u_g v_g w_g Q_{xj} Q_{yj} Q_{zj}]^T \quad (2)$$

where,  $\{F\}$  – vectors of force;  $F$  – force of number  $g$ ;  $x, y, z$  – axes;  $M$  – torque of number  $j$ ;  $\{\Delta\}$  – vectors of displacements;  $u, v, w$  – displacements along respective axes  $x, y, z$  of number  $g$ ;  $Q$  – angle of rotation on axes  $x, y, z$  of number  $j$ ;  $T$  – degrees of freedom. Based on the differential equation (3), the relationships between forces and displacements are written in the following form

$$\{F\} = \{k\} \cdot \{\Delta\} \quad (3)$$

where  $\{k\}$  - matrix of material strength.

For an element with  $n$  degrees of freedom, the differential equation assumes the form:

$$F_1 = k_{11} \cdot \Delta_1 + k_{12} \cdot \Delta_2 + \dots + k_{1n} \cdot \Delta_n \quad (4)$$

$$F_i = k_{i1} \cdot \Delta_1 + k_{i2} \cdot \Delta_2 + \dots + k_{in} \cdot \Delta_n \quad (5)$$

$$F_n = k_{n1} \cdot \Delta_1 + k_{n2} \cdot \Delta_2 + \dots + k_{nn} \cdot \Delta_n \quad (6)$$

According to the equilibrium conditions of the node, the external load  $P_i$  is equal to the sum of the internal forces (e.g. A, B, C, D) acting in the corresponding elements belonging to the node

$$P_i = F_i^A + F_i^B + F_i^C + F_i^D \quad (7)$$

Hence:

$$P_i = K_{ij} \cdot \Delta_i + K_{12} \cdot \Delta_1 + K_{i2} \cdot \Delta_2 + \dots + K_{i11} \cdot \Delta_{11} \quad (8)$$

where,  $K_{ij}$ - general strength coefficient;  $i$  – index determining force, for which the equation is true;  $j$  – index corresponding to the degrees of freedom.

The motion of each node is described by displacements in the X, Y and Z directions (degrees of freedom). Knowing the load in each node of the model, the differential equation for the three-dimensional case was worked out:

$$\begin{cases} \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + X = 0 \\ \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yz}}{\partial z} + Y = 0 \\ \frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \sigma_{zy}}{\partial y} + Z = 0 \end{cases} \quad (9)$$

where,  $X, Y, Z$  – mass forces;  $\sigma_x, \sigma_y, \sigma_z$  – stresses in a material layer;  $\tau$  – tangent stresses along axes  $x, y$  and  $z$ .

For the two-dimensional case, the following relationship holds true:

$$\begin{cases} \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + X = 0 \\ \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + Y = 0 \end{cases} \quad (10)$$

Linear relationships between deformations and displacements are written in the form:

$$\begin{aligned} \varepsilon_x &= \frac{\partial u}{\partial x}, \gamma_x = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \\ \varepsilon_y &= \frac{\partial v}{\partial y}, \gamma_y = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial y} \\ \varepsilon_z &= \frac{\partial w}{\partial z}, \gamma_z = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \end{aligned} \quad (11)$$

where,  $\varepsilon_x, \varepsilon_y, \varepsilon_z$  – relative deformation along axes  $x, y$  and  $z$ , respectively;  $\gamma_x, \gamma_y, \gamma_z$  – shear angle on axes  $x, y$  and  $z$ , respectively.

Based on the values of the stress-strain state and the material's strength parameters, the equivalent stress at certain nodes of the structure can be determined, according to the following formula [13]:

$$\sigma_0 = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \quad (12)$$

where  $\sigma_1, \sigma_2, \sigma_3$  – main stresses, MPa.

### 3.2. Determining stresses in the layer of samples made of MM "Stahl 1018" using the program "SolidWorks Simulation"

The presented method can be used for calculating the loads acting in different directions [15]. To determine the dependence of stresses on the coefficient of friction, a normal force was applied to the upper part, the lower part was set, and the possibility of moving the steel bases along the specimen element was blocked. To better evaluate the effect of stress on the development of deformations in the sample made of MM "Stahl 1018", an external load was applied to the upper surface of the mounting part ( $F=150$  kN) (Figure 4).

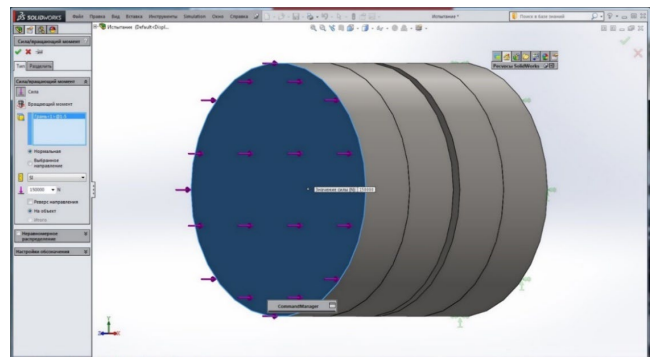


Fig. 4. Introducing load to the assembly

The simulation was preceded by creating a grid, the characteristic of which is shown in Table 3.

Table 3.  
Characteristic of the created grid

Name	Statistical analysis
Type of mesh	Solid mesh
Partition	Standard
Automatic densification of mesh	Out
Automatic mesh cycles	Out
Jacobian points	4
Size of object	1.11781mm
Tolerance	0.0558907mm
Quality of mesh	High
Total nodes	330519
Total positions	236384
Maximum coefficient of proportionality	4.3817
Percentage of elements with coefficient of proportionality below 3	99.9
Percentage of elements with coefficient of proportionality higher than 10	0
Percentage of deformed elements	0
Recreate grid	out

## 4. Results and discussions

### 4.1. Determining stresses acting on layers of specimens made of MM "Stahl 1018" simulating one- and two-sided connections using "SolidWorks Simulation 2019" software

Based on the simulation results, images (Fig. 5a-c) showing the stresses for three specimens with a two-sided contact between the polymer material and the metal base were generated.

The analysis of Figure 5 reveals that the stresses in the specimens imitating the two-sided contact model are unevenly distributed in the composite area. The maximum values are reached in the center of the lateral surface (red color), the stresses on the surface of the specimens closer to its center reach values from 230MPa to 240MPa and are almost twice as low as the maximum, which ranges from 410MPa to 425MPa. The distribution of stresses in specimens of different heights is similar, ranging from 64MPa (for  $H = 1.5\text{mm}$ ) to 76MPa (for  $H = 4.5\text{mm}$ ), with the maximum stress increasing proportionately to the height of the specimen. For specimen heights of  $H = 3\text{mm}$  and  $4.5\text{mm}$ , the maximum stress distribution ranges from 307MPa to 310MPa and occurs over a much larger area of the lateral surface, indicating a decrease in

composite strength for specimens with heights of  $H=3\text{mm}$  and  $H=4.5\text{mm}$ .

The next series of simulations was carried out for specimens with one-sided contact between the composite sample and the metal surface, using previously created specimen models. The specimens were mounted on a support, while applying a load of 150kN at its top (Figure 5 (d-f)). The results of the simulations showed that the distribution of stresses in the composite for two-sided contact specimens ranges from 180 MPa (for  $H = 1.5\text{mm}$ ) to 230MPa (for  $H = 4.5\text{mm}$ ), whereas the maximum stresses concentrate at the edge closer to the steel base and are much higher than in the middle part, ranging from 380 MPa (for  $H = 1.5\text{mm}$ ) to 425MPa (for  $H = 4.5\text{mm}$ ). This suggests that a reduction in the friction coefficient between the surface of the composite specimen and the surface of the steel base led to a reduction in the stress concentration near this surface. The magnitude of the maximum stress in this case increased to 425MPa, indicating a decrease in the strength of samples with one-sided contact as compared to those with its two-sided counterpart. Tests for specimens with a one-sided contact with a height of  $H = 3\text{mm}$  and  $H = 4.5\text{mm}$  confirmed these indicators.

All previous simulation results were obtained for a temperature of  $20^\circ\text{C}$ , whereas the next series of stress distribution tests were performed for elevated temperature conditions.

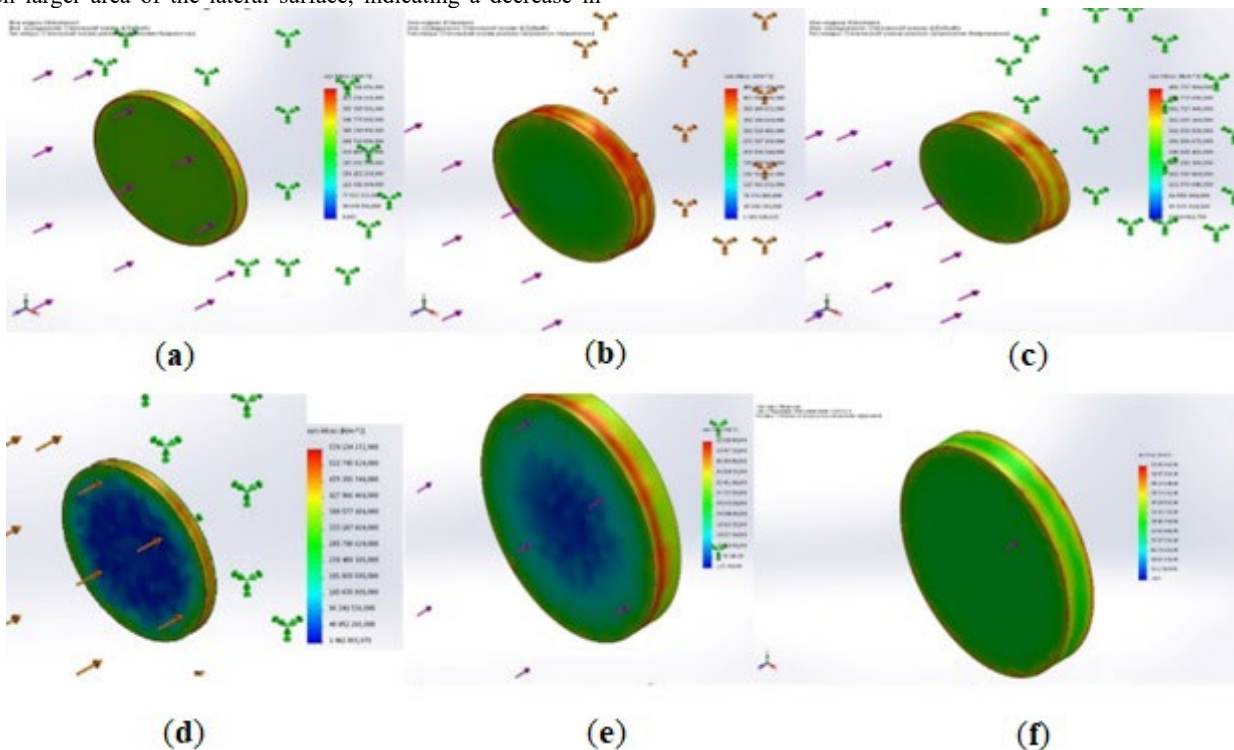


Fig. 5. Stresses acting in the layers of the sample simulating two- and one-sided contact joints

(a) sample simulating two-sided contact, sample height  $H = 1.5\text{mm}$ ; (b) sample simulating two-sided contact, sample height  $H = 3\text{mm}$ ; (c) sample simulating two-sided contact, sample height  $H = 4.5\text{mm}$ ; (d) sample simulating one-sided contact, sample height  $H = 1.5\text{mm}$ ; (e) sample simulating one-sided contact, sample height  $H = 3\text{mm}$ ; (f) sample simulating one-sided contact, sample height  $H = 4.5\text{mm}$ ;



## 4.2 Determining stresses arising in the layer of specimens made of MM "Stahl 1018" in a free state and partially clamped in a steel base using the program "SolidWorks Simulation 2019"

Another type of specimens for which simulations were performed in "SolidWorks Simulation 2019" were MM "Stahl 1018" specimens, partially placed in a steel base. The depth of fit to the steel base was  $h = 2$  mm, and the excess was  $H = 1.5$ mm,  $H = 3$ mm and  $H = 4.5$ mm for each of the three specimens, respectively. Before testing, the specimen was fixed in the lower support and a load of 150kN was applied to its upper part, then a computing grid was created and simulations were carried out. The results of the calculations are shown in Figure 6.

The experimental results reveal that the stresses in the composite sample placed in the steel base are up to 460MPa and are much higher than in the metal base (up to 53MPa), and the zone of maximum stress is located at a distance of 1-2 mm along the

entire periphery of the sample, similar to that in samples with a one-sided contact. The stress concentration has a similar pattern to the results shown in Figure 5 (d-f) illustrating the stress distribution in specimens with a one-sided contact. The stresses shift toward the lateral edge and the presence of maximum stresses at the visible boundary of the sample made of MM "Stahl 1018" material were also observed. The magnitude of the maximum stresses and strains, compared to the single contact, slightly decreased from 425MPa to 403 MPa (Figure 6 (a-c)).

The final step lied in checking the character of the distribution and magnitude of stresses for cylindrical specimens in a free state. The resulting stress distribution diagrams are shown in Fig. 6 (d-f). The stress distribution in the free-state specimens is identical to that of specimens with one- and two-sided mounting (Figure 5). Note that the accumulation of maximum stresses on the lateral surface is an order of magnitude lower than in specimens with one- and two-sided mounting, at 275MPa, and the value of maximum stresses is 310 MPa, which is higher than in specimens with one- and two-sided loading and partly clamped in a metal base (284MPa).

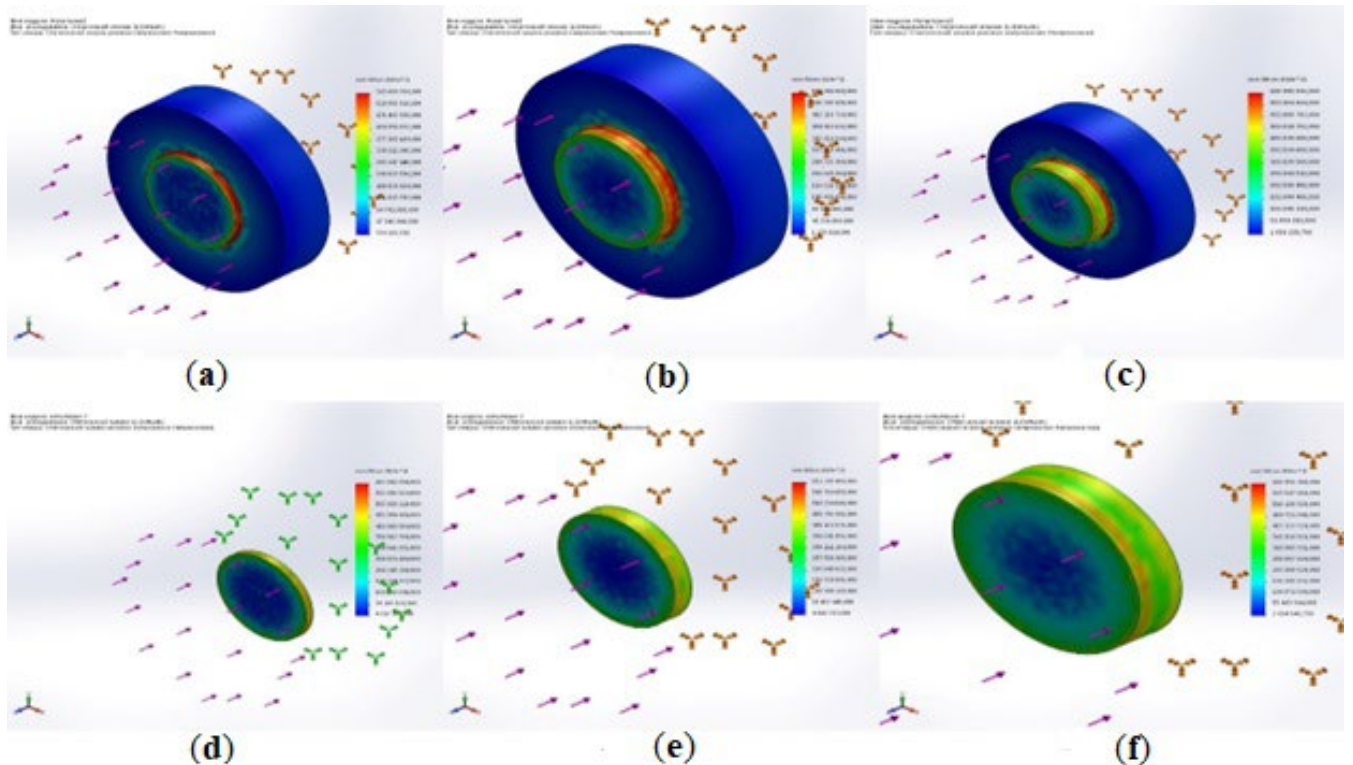


Fig. 6. Graphical representation of the stresses acting in the composite layers, in a free state and partly clamped in a steel base (a) sample clamped in steel base, sample excess height  $H = 1.5$ mm; (b) sample clamped in steel base, sample excess height  $H = 3$ mm; (c) sample clamped in steel base, sample excess height  $H = 4.5$ mm; (d) sample in free state with sample height  $H = 1.5$ mm; (e). Free state specimen with specimen height  $H = 3$ mm; (f) free state specimen with specimen height  $H = 4.5$ mm.

### 4.3 Simulation of mechanical strength of specimens made of MM "Stahl 1018" under elevated temperature conditions in the program "SolidWorks Simulation 2019"

The tests were performed for samples from MM "Stahl 1018" in a free state, and for samples partly disposed in a steel base. The temperature dependence of the strength of the specimens was theoretically tested in the following way: a load was applied to the top of the specimen in the range of 10 to 40kN in 10kN increments, and the operating temperature was of 20-80°C. The stress value corresponding to 0.2% of the thickness of the composite material was taken as the conventional yield strength. Figure 7 presents the grid design for which simulations were carried out with the given specimen parameters (D = 20mm; H = 1.5mm, H = 3mm, H = 4.5mm).

Graphs in figures 10-12 show the dependence of maximum stress in a specimen made of MM "Steel 1018" with a height of 1.5; 3 and 4.5mm and at temperatures of 20; 40; 60 and 80°C. For a 1.5 mm high specimen (Figure 10) the curves drawn for 20°C and 40°C intersect in the range of 25kN and 30kN, indicating that the material is more brittle at room temperature; as the load increases, the maximum stress increases faster. At 40°C, the composite is more flexible while retaining its strength properties. On the other hand, when the temperature grows to 60°C and then to 80°C, the stresses are 370MPa and 410MPa for a load of 40kN, and higher than for 20°C (300MPa) and 40°C (270MPa). Taking into account the fact that the material will be used in real conditions at temperatures up to 70°C, the composite is expected to fail at a stress of 400MPa. The analysis of the obtained data reveals that the stress in the sample increases with increasing temperature. This is due to the thermal stresses development in the composite, which contributes to the stress increase. This means that the mechanical properties of the material change under high temperature conditions

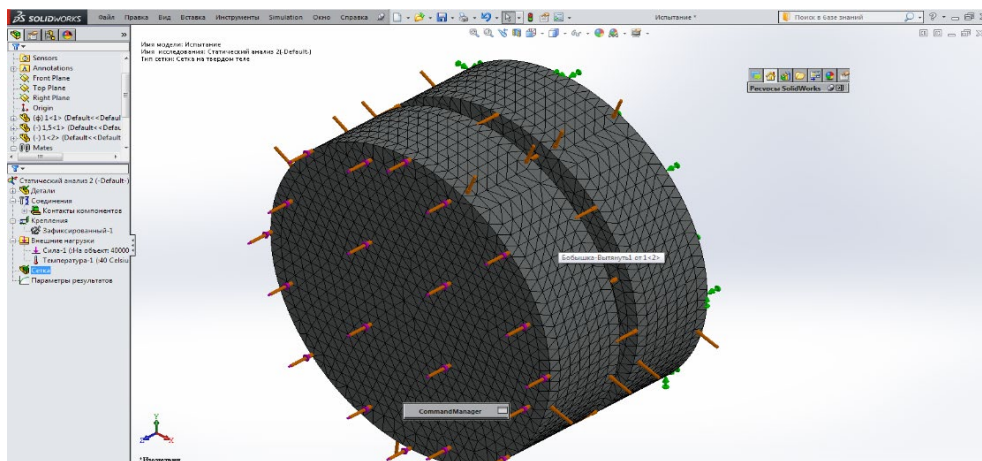


Fig. 7. Calculation grid (high grid quality)

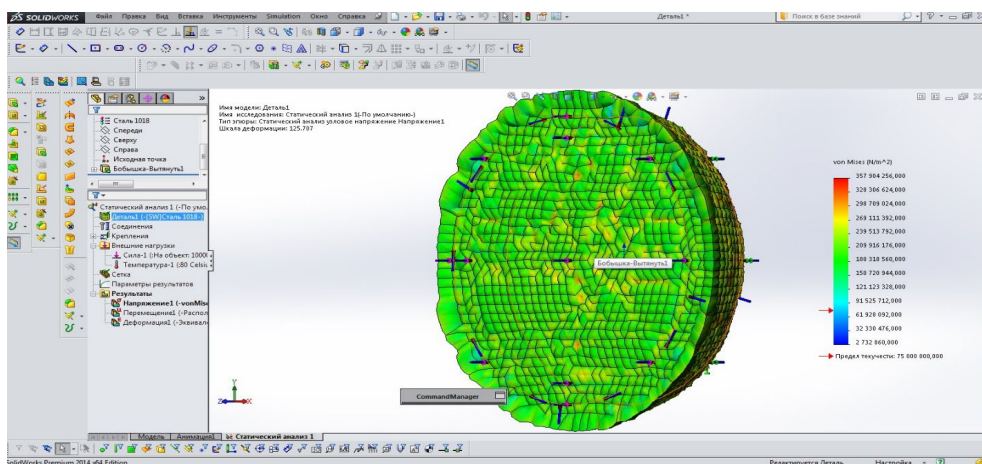


Fig. 8. Graphical representation of the stresses acting in a sample (H = 3 mm; T = 80°C)

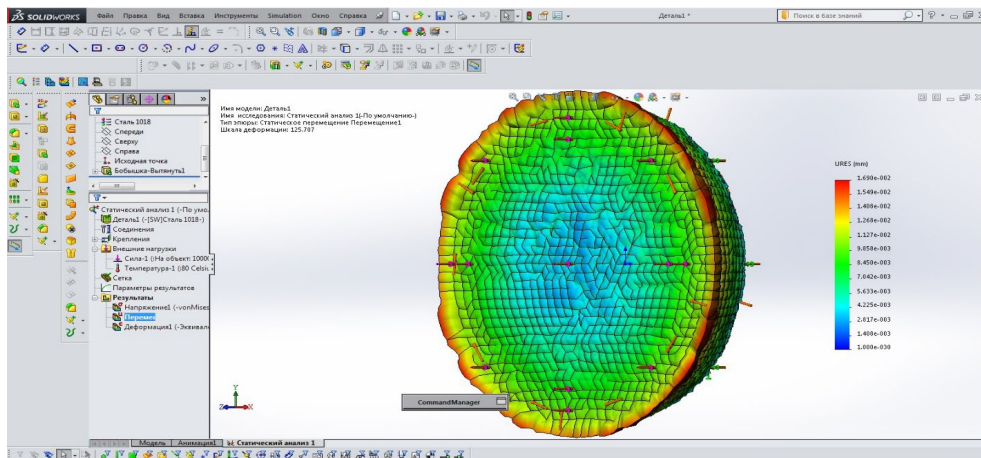


Fig. 9. Graphical representation of displacements in a sample (H = 3 mm; T = 80°C)

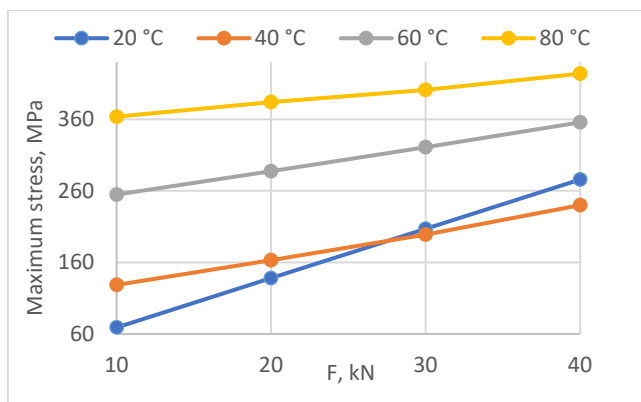


Fig.10. Maximum stress in a 1.5mm high specimen made of MM "Steel 1018" at temperatures of 20°C, 40°C, 60°C and 80°C

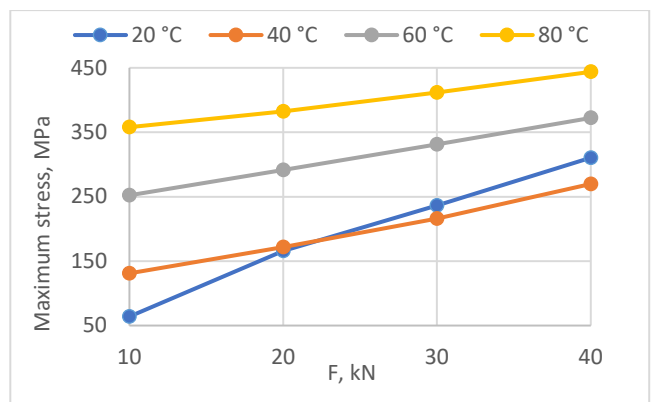


Fig. 12. Maximum stress in a 4.5 mm high specimen made of MM "Steel 1018" at temperatures of 20°C, 40°C, 60°C and 80°C

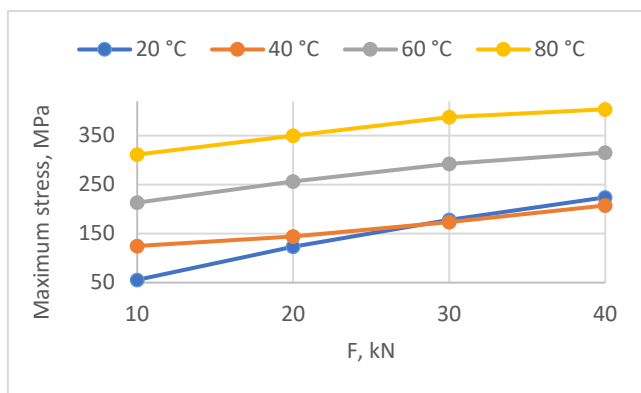


Fig. 11. Maximum stress in a 3mm high specimen made of MM "Steel 1018" at temperatures of 20°C, 40°C, 60°C and 80°C

As the height of the samples increased to 3 mm (Figure 11) and 4.5 mm (Figure 12), the maximum stresses grew up to 430MPa and 450 MPa, respectively. The experiments showed that the specimen material with a height of 4.5mm and at 80°C could withstand stresses up to 430MPa.

The next step in the analysis of MM "Stahl 1018" was to identify the compressive strength with partial confinement of specimens in a metal base under high temperature conditions. The study was also performed with the "SolidWorks Simulation 2019" program. Computer simulations showed that specimens made of MM "Stahl 1018" with partial fixing of the composite material in the metal base at elevated temperatures show less shrinkage as compared to samples in the free state. There is also a significant reduction in stresses in the composite layer. At the same time, there is a significant decrease in strength with increasing temperature.

Figures 13-15 show the dependence of the maximum stress in a specimen made of MM "Steel 1018" composite with a height of 1.5 mm, 3 mm and 4.5 mm, partly confined in a metal base and at temperatures of 20°C, 40°C, 60°C and 80°C. For the 1.5mm high specimen (Figure 13), the lines of the dependence of maximum stress on load for temperatures of 20°C and 40°C are parallel. This can be explained by the fact that the specimen is encapsulated in the metal base to a height of 1 mm and only 0.5mm is loaded. With such a small height, the temperature difference is equalized, but nevertheless the stress at 40°C increased from 143MPa to 180MPa. Approximately the same course is observed at 60 °C and 80 °C. The maximum stress at 40kN load and 80°C was 309MPa. For



comparison's sake, the stress in a 1.5mm high specimen in the free state at the same parameters was 424MPa, i.e. 27.2% higher.

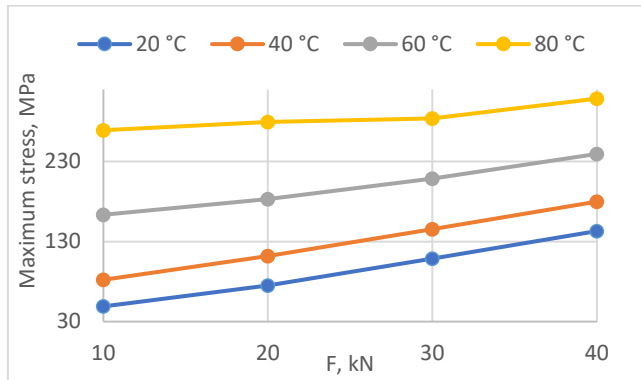


Fig.13. Dependence of the maximum stress in a 1.5 mm high specimen made of MM "Steel 1018" partly encapsulated in the metal base at temperatures of 20°C, 40°C, 60°C and 80°C

For a 3mm high specimen (Figure 14), a similar trend is observed as in the cases shown in Figures 11-13. The result obtained for a temperature of 80°C with a load of 40kN is particularly interesting as here the maximum stress in the specimen equaled to 404MPa. The 3mm high specimen is embedded in the steel base to a height of 1mm, so 2mm of it remains in the free state, giving a result by 6% lower than for its 1.5mm high counterpart under the same conditions, but in the free state.

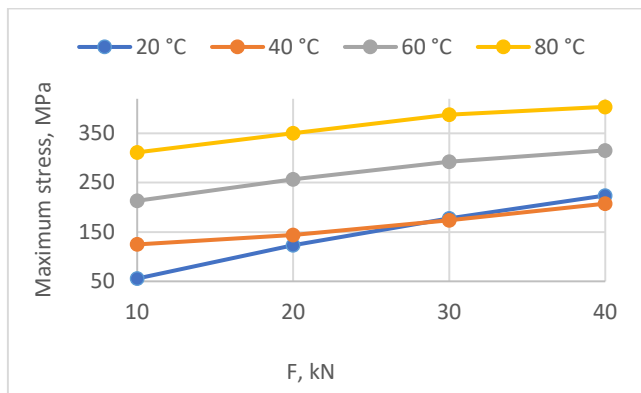


Fig. 14. Maximum stress in a 3 mm high specimen made of MM "Steel 1018" partly enclosed in a metal base at temperatures of 20°C, 40°C, 60°C and 80°C

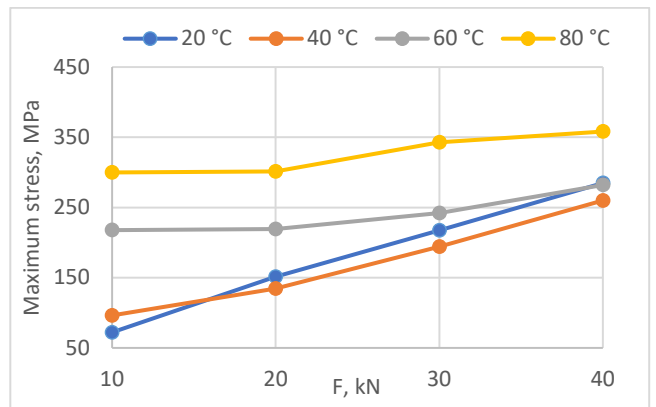


Fig. 15. Maximum stress in a 4.5 mm high specimen made of MM "Steel 1018" partly enclosed in a metal base at temperatures of 20°C, 40°C, 60°C and 80°C

The analysis of Figure 15 reveals that in the case of a 4.5mm high specimen exposed to a load of 40kN and temperatures of 20°C, 40°C, 60°C all the lines of the dependence of the maximum stress in the specimen on the applied load are reduced to almost one point. This suggests that the effect of temperature levels out with the growing load. However, for a temperature of 80°C, the maximum stress was 358MPa, i.e. higher by 74MPa than at 60°C. This indicates that the specimen gradually softened with the increasing temperature, but the maximum stress was still 19.3% lower than for a 4.5mm high specimen in the same conditions, but in the free state.

## 5. Conclusions

1. With the decreasing coefficient of friction of the contacting surfaces of the MM "Stahl 1018" specimen against the preserved steel surface, the stresses in the composite layer increase from 64MPa (for height  $H = 1.5\text{mm}$  and temperature  $T = 20^\circ\text{C}$ ) to 444MPa (for height  $H = 4.5\text{mm}$  and temperature  $T = 80^\circ\text{C}$ ).
2. Theoretically, the sample layer of MM "Stahl 1018" material, which closely adheres to the surfaces of the steel bases on both sides (444MPa), has a higher maximum strength than the material layer contacting with one surface (358MPa), for specimens with a height of 4.5mm and a temperature of 80°C.
3. Simulations revealed a significant increase in the maximum stress in the MM "Stahl 1018" for specimens in the free state (from 285 MPa to 358 MPa) with the increasing temperature from 20°C to 80°C, for specimens with height  $H = 4.5\text{mm}$ .
4. The analysis of the results of Table 3.5 shows that the stresses and displacements in the layer of MM "Stahl 1018" composite partly embedded in a metal base are 19.3% and 32.4% (from 444MPa to 358MPa and from 0.0549mm to 0.0371mm) are lower than the material in the free state.
5. Connecting two steel bases with MM "Stahl 1018" increases the values of mechanical parameters of the joint, which is indicative of properties of a highly simplified laminate composite. This means that an increase in the number of layers results in an increase in mechanical parameters.

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## References

- [1] Sołek, K., Kalisz, D., Arustamian, A. & Ishchenko, A.A. (2017). Analysis of strength characteristics of composite materials under vibration loads at higher temperatures. *Journal of Machine Construction and Maintenance – Problemy Eksploatacji* 93-97.
- [2] Arustamian, A., Sołek, K. & Kalisz, D. (2016). Identification of yield point of polymer – based composite material in the conditions of increased temperatures. *Archives of Metallurgy and Materials*. 61(3), 1561-1566. DOI: 10.1515/amm-2016-0255
- [3] Kalisz, D. & Arustamian A. (2020). Multimetal Stahl 1018 composite – structure and strength properties. *Archives of Foundry Engineering*. 20(4), 29-35. DOI: 10.24425/afe.2020.133351.
- [4] Ischenko, A.A. (2012). Technological bases of restoration of the industrial equipment by modern polymeric materials PSTU (Mariupol). 27-39.
- [5] Donev, K.V. (2007). Investigation of the properties of metalpolymer materials and the development of technology of repair roughing stand. Master's thesis, PSTU, Mariupol, Ukraine.
- [6] Vorona, A.S. (2009) Theoretical and experimental research of the mechanical properties of polymer repair materials for different purposes. Master's thesis, PSTU, Mariupol, Ukraine.
- [7] Kalinichenko, S.A. (2003) Research of the dynamic properties of metal-polymer materials. Master's thesis, PSTU, Mariupol, Ukraine.
- [8] Timoschenko, A.V. (2010) Research of the mechanical properties of composite materials under dynamic loading. Master's thesis, PSTU, Mariupol, Ukraine.
- [9] Kakareka, D.L. (2013) Research of the mechanical properties of composite materials under dynamic loading. Master's work, PSTU, Mariupol, Ukraine.
- [10] Arusrtamian, A. (2023). *Modeling and analysis of the mechanical properties of the composite based on a polymeric material used for the maintenance of metallurgical equipment*. Doctoral thesis, AGH, Krakow, Poland.
- [11] Diamant. Polymer Solutions. (2024). Retrieved January, 20, 2024, from <http://diamant-polymer.de/en/products/mm1018/> 11.
- [12] DIN EN ISO 604:2003-12, 2003.
- [13] Stal C45 PN-EN 10083-2:1999
- [14] Solidworks.(2024). Retrieved January, 20, 2024, from <https://discover.solidworks.com/>
- [15] Solidexpert. (2024). Retrieved December, 10, 2024 from <https://solidworks.agh.edu.pl/>