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Original scientific paper

Application of Natrium Silicate as a Phase Change Material in Fixture Design

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Abstract: The paper presents the results of theoretical, numerical, and experimental research related to the analysis of the possibility of using natrium silicate in the design of fixtures. Two possible aggregate states of natrium silicate (liquid and solid aggregate state) with its strong adhesion to metal materials as well as a number of other properties were used, and it was proven that it can find significant applications in the fixture of workpieces, especially when machining workpieces with thin walls and complex contours, as well as pockets with a large pocket depth to wall thickness ratio. The results of the performed analyses indicate a great potential for the application of natrium silicate as a new phase-change material. A mixture of natrium silicate and non-metallic materials such as fireclay flour acquires the properties of stone by hardening, while it decomposes when in contact with water. This mixture can solve the problems of technological operations on workpieces with thin walls and closed contours, known as deep pockets. The research results related to the proposed machining method were verified by using the example of machining a deep pocket with a complex contour. After the process of machining the complex contour of the thin-wall workpiece, the meanwall thickness value of 0,144 ± 0,004 mm at the meanpocket depth value of 60,052 ± 0,058 mm was obtained. The obtained mean values of the pocket depth and wall thickness as well as their mutual relationship, indicate the possibility of the practical application of natrium silicate as a phase-change material in the fixture design for machining thin-wall workpieces of complex geometry.

Keywords: fixture design; natrium silicate; thin wall

1 INTRODUCTION

Machining processes are characterized by increasing demands regarding the quality of the manufactured parts, achieving high productivity, and the productivity of the machining systems. When it comes to machining systems in the field of machining, it can be said that fixtures represent the weakest link of the machining system: the machine-cutting tool-fixture. In a large number of cases of production operations, fixtures in production conditions, from the aspect of performance (stiffness, flexibility, structural stability), cannot follow the development of machine tools and new cutting tools [1, 2]. In a certain way, fixtures, especially in the machining operations of thin-wall workpieces, represent a bottleneck in the machining process, where the limited rigidity and dynamic stability of the fixture limit the great potential of machine tools and cutting tools that work at significantly lower loads than are realistically possible [3, 4]. When machining thin-wall workpieces, phase-change fixtures are very common.

The fixture serves to ensure the correct and stable position of the workpiece during machining [5]. In order to effectively respond to this demand, manufacturers must ensure that their products are sufficiently flexible for production and can allow rapid product development [6]. An appropriate fixture design can improve the quality and machining process of workpieces and facilitate the exchange of workpieces, which is very important in modern production [7]. In order to ensure the rigidity of the workpiece during machining, this implies the use of fixtures that can be disassembled into modules and reassembled into the required fixture for the appropriate shape of the workpiece [8, 9]. For this purpose, phase-change fixtures are used.

A phase-change fixture is a device that can hold workpieces of various shapes and sizes while they are exposed to a large number of different manufacturing operations [10-12]. A flexible fixture is a very important item in any production cycle, where one set of clamping fixtures is used to center and support various workpiece shapes. A flexible fixture with phase-change materials includes the use of functional materials that change their aggregate states from liquid to solid and vice versa when induced by certain external conditions [13]. The mentioned phase change must be controlled in a simple way, and its harmful effect on the workpiece is almost non-existent. The application of this fixture method takes place in two steps. The workpiece is placed in a liquid flexible material and remains solidified when the material transits to a solid state. After the machining process, the phase change material is returned to the liquid state in order to remove the workpiece from the fixture.

Natrium silicate is used on a large scale in industry as a sealant, adhesive, deflocculant, emulsifier, and shock absorber in the foundry industry, as well as for various academic research [14-28]. The common feature of all forms of natrium silicate is their solubility in water with the formation of a glassy emulsion [21-23]. It most often appears in the chemical form Na_2SiO_3 and $Na_2SiO_3 \cdot 9H_2O$. It is formed in the reaction of melting natrium carbonate and silicon dioxide with the release of carbon dioxide: $Na_2CO_3 + SiO_2 \rightarrow Na_2SiO_3 + CO_2$.

The properties of natrium silicate as an adhesive have been known for years [24-26]. Research based on the use of natrium silicate gel as a binder for cold curing was described by Kouassiet al. [24]. Binding materials were obtained by mixing natrium silicate with granular materials (silicon powder and sand) before cooling. It is most often used as an inorganic binder. It has proven to be very useful because in the agglomeration process it combines and consolidates fine and small particles into larger groups, as the silicate reacts with the surface of the particles. Kouassi et al. [24] showed the good properties of natrium silicate as an adhesive even at low temperatures. Natrium silicate as a glue uses the so-called "sponge effect" and behaves like an absorbent water film. This adhesive ability can be used successfully in various fields. Natrium silicate breaks down in water. After the hardened natrium silicate gets wet, part of the water combines with the disilicate unit and forms $NaHSi_2O_5$, while the other part hydrates the silicate [26]. The static and dynamic viscosity of the natrium silicate solution with changes in temperature, modulus, shear rate, and chemical additive concentration was examined in the paper [27]. The static results showed that the viscosity increases monotonically while the concentration of the solution varies in the range from 15 to 55%, decreases with increasing temperature from 15 to 70 °C, and has a minimum value when the modulus is 1,8. These results suggest that the natrium silicate solution exhibits the properties of a suspension, in which the silicate anions act as a binder and the colloidal particles act as effective stiffeners. The thermal treatment of natrium silicate presented in paper [28] provides data related to natrium silicate and phase transitions from 100 °C to 800 °C, which provide useful information about the stability of this compound and its use at different temperatures.

The problems of machining thin-wall workpieces represent a very current area of research. Herranz et al. [29] proposed a working methodology for efficient process planning based on a preliminary analysis of static and dynamic phenomena that can occur during high speed machining and proposed a method that includes: several steps to minimize the effects of bending and vibration; optimal monitoring methods for detecting process instabilities, and choosing the optimal choice of cutting conditions through simulations of different machining stages. Argha et al. [30] presented a systematic comparative study of different approaches to machining. They studied and compared five machining approaches and analysed their effect on the wall thickness of the workpiece and the quality of the machined surface. Gururaj et al. [31] presented a study on the influence of machining parameters, i.e., feed per tooth and axial depth of cut, on the surface integrity and accuracy of the dimensions in thin-wall machining. Ratchev et al. [32] addressed advanced prediction and compensation strategies for errors arising as a consequence of the action of cutting forces in the machining of thin-wall workpieces. Machining error is predicted using a theoretical flexible force-deflection model and compensated for by optimizing the toolpath. The results of the experimental verification of the proposed routines indicate the possibility of reducing the surface profile error from an average of 21% to 6%. The properties of natrium silicate and the possibility of its wide application lead the authors of this paper to conclude that this very available substance can be used as a phase-change medium in fixtures. Rong et al. [11] presented an experimental study of a magnetorheological (MR) fluid material. MR fluids have been studied experimentally for potential applications in flexible fixation. The compression technique is applied to significantly increase the yield strength of the MR liquid in the solid state. A high shear strength of 800 KPa was achieved, which could be higher if the test conditions were improved. Tang et al. [33] studied the application of MR-fluid-flexible fixtures. The MR fluid has a rapid phase change and high yield strength. The yield strength and modulus of elasticity before stretching are key issues for flexible reinforcement. However, a typical MR fluid currently has a yield stress of about 100 KPa, which is not sufficient for flexible elements. To overcome these difficulties, they applied single pressure chains that generate a pressure stress of 800 KPa or more under a moderate magnetic field. Croppi et al. [34] presented a general methodology for the optimization of reinforcement in cases of turning thin-wall workpieces. Starting from the geometry of the workpiece and the tool path, by combining the FE model, the geometric error model, and the fixture model, the optimal configuration of the fixture is calculated as the one that can guarantee the imposed tolerance and stable machining with a minimum number of additional supports. Popov et al. [35] took into account the general principles and proposed new strategies to reduce the negative effects of the identified factors on workpiece quality and, at the same time, to overcome some of the problems associated with the use of conventional machining strategies for micromilling ribs and webs. Kolluru et al. [36] presented a novel surface damping solution that can be applied to thin-wall complex housings to minimize machining vibrations. The main advantage of the proposed solution is the possibility of applying it to complex elements. The proposed solution for damping was tested in terms of its effectiveness when testing the dynamic impact during machining. Zawada-Michałowska et al. [37] studied and examined the influence of selected machining techniques and technological heritage of semi-finished products on the deformations of thin-wall workpieces. They applied techniques such as high performance machining, high speed machining, conventional finishing, and combinations of these techniques. It was hypothesized that it may be relevant in relation to the direction of movement of the cutting tool and consequently has a significant effect on the stress as well as the deformation after machining. The analysis of the obtained results showed that machining in the direction perpendicular to the rolling direction results in greater deformations than machining in the parallel direction. In addition, it was discovered that the application of a properly selected machining technique enables the minimization of post-machining deformations of thin-wall workpieces. Izamshah et al. [38] developed an adapted design geometry of a variable helix milling cutter for the machining of thin-wall aerospace components. In their research, they showed that by manipulating the design of the inclination and the cutting helix of the milling cutter, the size of the surface error can be reduced compared to the geometry of the milling cutter with a constant helicoidal helix and a constant inclination.

An analysis of the literature shows that the level of development of these fixtures in terms of greater industrial application is not at a desired level. The authors of these works emphasize and try to solve the problems of machining errors, the quality of the machined surface, and the problems of vibrations. It can also be said that existing phase-change materials are not characterized by a desired level of magnitude of the parameters that define their mechanical characteristics.

Based on the analysis of the literature, the authors of the paper believe that natrium silicate has a number of characteristic properties that can expand the area of its application in many spheres. A particularly important property of natrium silicate, from the aspect of its application in fixtures as a phase-change material, is that when it is combined with fireclay flour, the mixture takes on the properties of stone after drying in air or at elevated temperatures, which is known in the literature. This mixture is soluble in water like natrium silicate. Also, natrium silicate has good mechanical properties as an adhesive that, through adhesion forces, ensures a high load capacity under the effect of tangential and normal loads.

2 PRELIMINARY RESEARCH

Experimental research was carried out in order to determine the mechanical characteristics of natrium silicate as an adhesive with two aggregate states and to determine the potential application possibilities of this material in the fixture design. The bearing capacity of the glued joint of samples of two metal materials was determined experimentally. Natrium silicate is used as a glue. The load-bearing capacity of glued joints is examined from the aspect of shear and normal (tensile) bond breaking stress. Fig. 1 shows the CAD model of the purpose-built test device, photographic representation of the device, CAD detail of the bond breaking zone under the action of shear stress, and photographic representation of the samples after breaking the bond. Fig. 2, by analogy with the previous figure, shows the CAD model of the used device, a photographic view of the used device, CAD detail of the connection break zone, and the samples used for determining the bearing capacity of the joint from the aspect of normal tensile stresses.

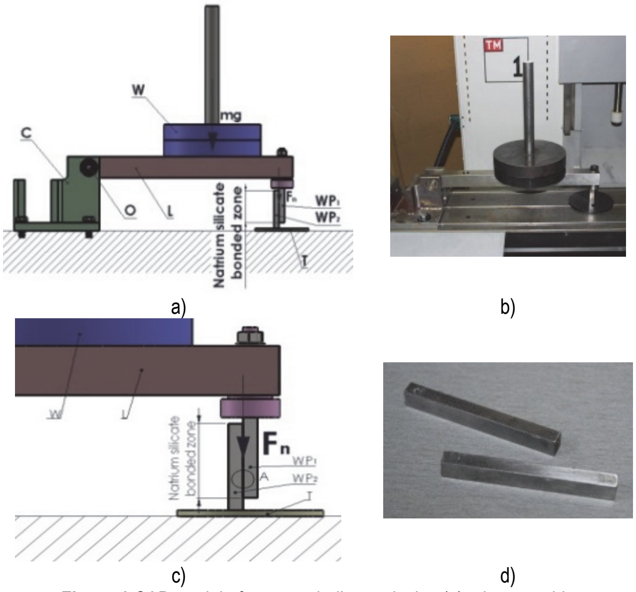


Figure 1 CAD model of purpose-built test device (a); photographic representation of the device (b); CAD detail of the bond breaking zone under the action of shear stress (c); photographic representation of the samples after breaking the bond (d)

The bond is loaded by the force created in the process of the weight acting on the vertical glued joint via the lever mechanism *L* and the balanced weights *W*. The bond breaking force F_n depends directly on the strength of the bond between the natrium silicate and the metal samples. The lever mechanism *L* is rotatable around the point *O* via the bearing in that joint, which carries the bolted device support *C*. The contact pairs WP_1 and WP_2 are supported on a flat steel base *T*. The contact load F_n is carried out precisely by the real static force that arises in the process of shearing or stretching. The maximum force occurring in the connection of the contact pairs WP_1 and WP_2, which are made of the desired material, which the connection made of natrium silicate can withstand before breaking the connection, is analysed.

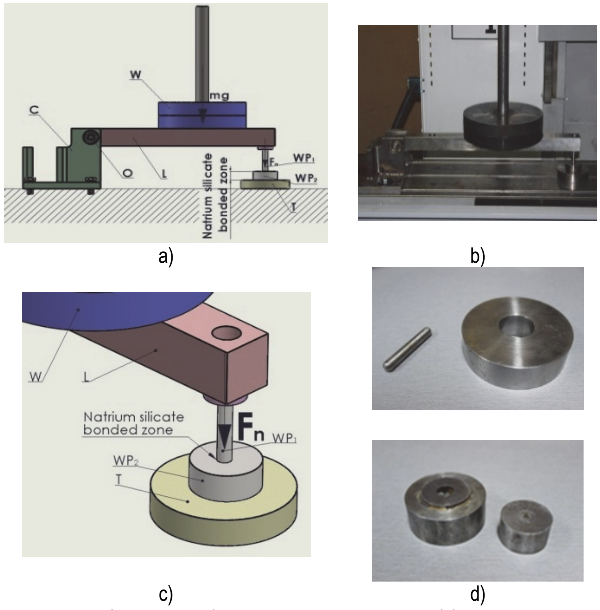


Figure 2 CAD model of purpose-built testing device (a); photographic representation of the device (b); CAD detail of the bond breaking zone under the action of tensile stress (c); photographic representation of the samples after breaking the bond (d)

Preliminary results of testing adhesiveness of natrium silicate. The test program includes two samples of natrium silicate "L1" and "L2". Fig. 3 and Fig. 4 show the normal and shear bond breaking stresses for two types of natrium silicate as a function of the heating time and temperature at which the joint was hardened.

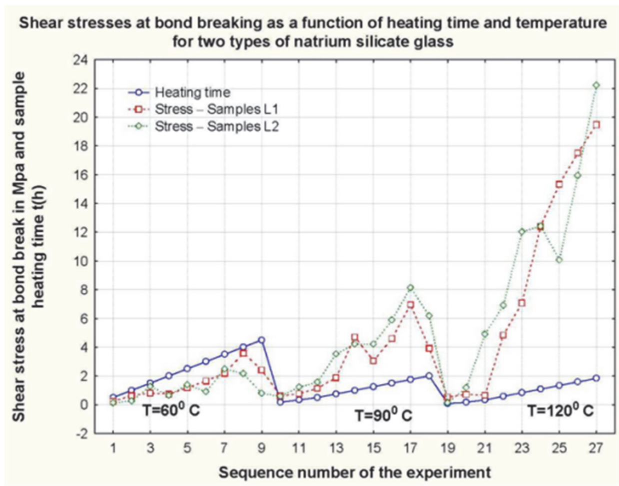


Figure 3 Bearing capacity of the joint from the aspect of shear stress

The natrium silicates (L1 and L2) were heated at temperatures of 60 °C, 90 °C, and 120 °C in a laboratory furnace with an adjustable temperature scale. For both natrium silicates, measurements were made with 30 samples each. Ten samples each were tested at temperatures of 60 °C, 90 °C, and 120 °C. The curing times of the natrium silicate samples are given on the ordinate of both diagrams (Fig. 3 and Fig. 4) and shown by blue lines. The stress measurement was performed by loading with weights. The load was increased up to the breaking point, and accordingly, the breaking load is expressed on the ordinate in MPa together with the time (h) of heating for the given sample. Fig. 3 for the shear results is related to Fig. 1, and Fig. 4 for the tensile results is related to Fig. 2.

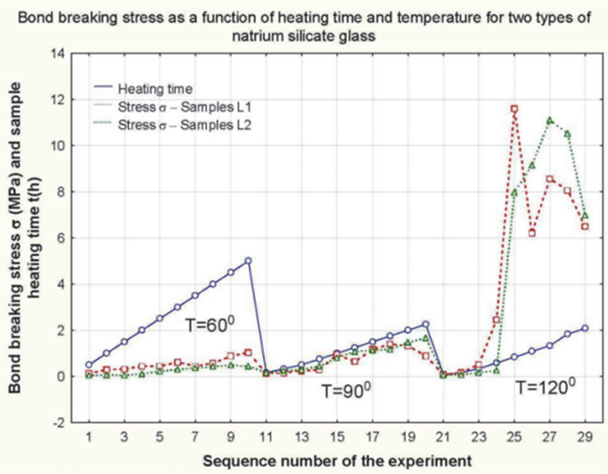


Figure 4 Bearing capacity of the joint from the aspect of tensile stress

3 THEORETICAL CONSIDERATIONS

The authors' idea related to the potential application of natrium silicate as a new phase-change material in the machining processes of deep pockets and thin-wall workpieces is explained by theoretical considerations related to the stress-deformation state of the workpiece under the action of cutting forces, which in production conditions have a pronounced dynamic component (Fig. 5).

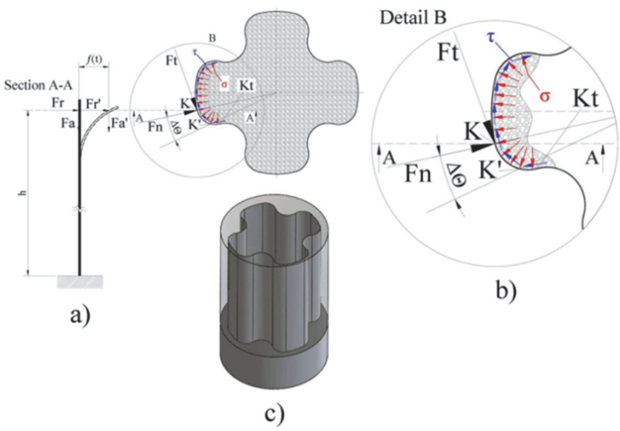


Figure 5 Stress and deformation state of the thin-wall workpiece of the closed contour during the machining. Cross section A-A of figure b (a); Magnified view of the workpiece from above (b); Isometric view of the workpiece with transparently marked edges of the workpiece before machining (c)

The key problem in the process of machining thin-wall workpieces is locating and clamping. When machining on the surface of the outer contour, the point of action of the cutting force "K" changes at every moment of time. In fact, the cutting force will change the point of attack during machining. This means that at each point of the "narrow zone" on the surface of the outer contour, at some point during the machining time, the cutting force will act. Object deformations during machining are also functions of time and relate to deflection $f(t)$ and twist angle $\theta(t)$. The size of the deflection $f(t)$ and the twist angle $\theta(t)$ are functions of time, that is, the coordinate of the actual cutting force, which changes during the machining. The magnitude of the deformations primarily depends on the stiffness and stability of the applied method of locating and clamping. The thin-wall workpiece should be reliably located and clamped over the entire surface of the inner contour.

The system of locating and clamping that is proposed implies the technological procedure of the previous production of the pocket (Fig. 5c). The machining of the pocket is carried out with high stability of the workpiece, which is ensured by the large cross-sectional area of the profile (Fig. 5c). A mixture of natrium silicate and fireclay flour is poured into the dug pocket. When the poured mixture hardens (in air or by heating at elevated temperatures), the machining of the outer contour is started. The performed preliminary experiments showed a strong adhesion between the natrium silicate and metal objects and very good mechanical characteristics (hardness, modulus of elasticity, etc.), which are known in the literature. It should be noted that the modulus of elasticity of the mixture of natrium silicate and fireclay flour is E = 21200 MPa. The preliminary experimental research showed that the shear stress of breaking the bond between natrium silicate and the aluminum sample reaches significant values of the order of 10 MPa (Fig. 3). The authors believe that there are virtually no essential limitations in terms of the possibility of achieving large ratios between the depth of the pocket and the thickness of the wall and achieving a high quality of machining. It is assumed that the experimentally obtained size of the shear bond breaking stress, of the order of 10 MPa, and the large contact area of the inner contour of the pocket "Kt" (Fig. 5, Detail B) and natrium silicate through adhesion forces at significantly lower stresses will balance the tangential force that twists the thin-wall workpiece and the error $\Delta\theta(t)$ related to deformations and angle change $\theta(t)$ to be reduced to a negligible value. Also, considering the mechanical characteristics of the mixture of natrium silicate and fireclay flour (E = 21200 MPa), the high value of the moment of inertia of the intersection of the thin wall and the mixture, and the size of the cutting forces, it is assumed that the deflection $f(t)$ will have a negligible value, which will greatly affect the accuracy of the production and the quality of the machined surface of the deep pocket.

4 NUMERICAL SIMULATION

Numerical simulations were performed for the deep pocket profile and the machining subject discussed in the previous chapter. The model of the final external machining of the thin-wall workpiece pocket (blue color) and the workpiece part that is not processed (graycolor) is shown in Fig. 6. The input data for the simulation were: the workpiece of aluminum (thin wall - blue color) and the part of the same workpiece that is not processed (grey color) also from aluminum, E = 70000 MPa, ν = 0,3, ρ = 2700 kg/m^3. The mixture of natrium silicate and fireclay flour was in the ratio 1:3 (transparent): E = 21200 MPa, ν = 0,24, ρ = 2810 kg/m^3.The simulated values of the cutting forces were increased by 45% compared to their calculated values, which correspond to the recommended parameters of the machining mode for the finishing of thin-wall workpieces. Simulated tangential force along the contour: F_T = 60 N; Simulated normal force along the contour: F_N = 30 N; Simulated axial force along the contour: F_Z = 60 N. Fig. 6 shows the mesh view of the model.

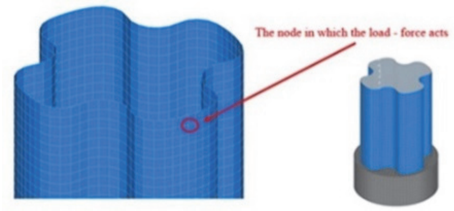
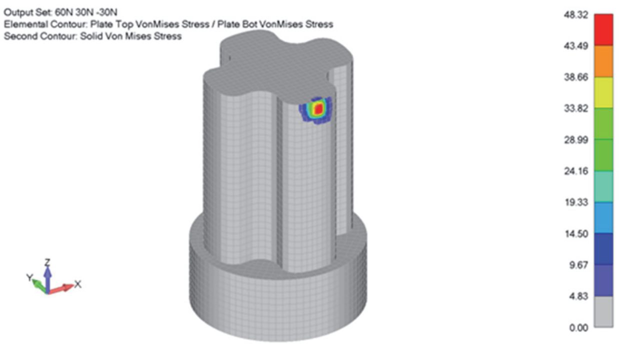


Figure 6 Mesh view of the machining workpiece

The representation of the field of Von Mises stresses along the contour of a thin wall is given in Fig. 7, while the field of deformations caused by the action of cutting forces is shown in the diagram in Fig. 8.



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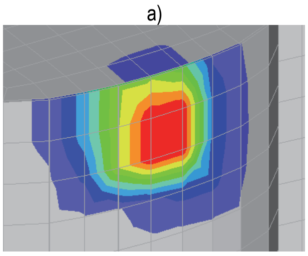
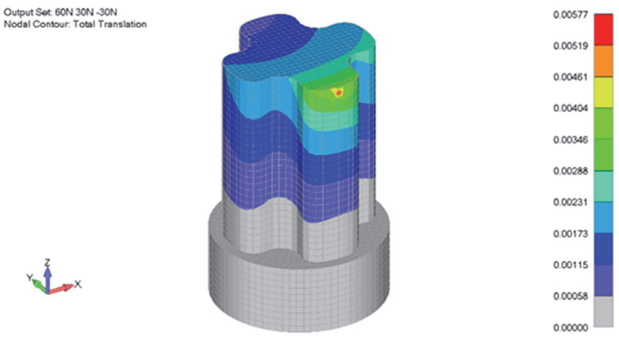


b)

Figure 7 a) Stress field-Whole model; b) Magnified detail of the workpiece on which the tool load acts during machining



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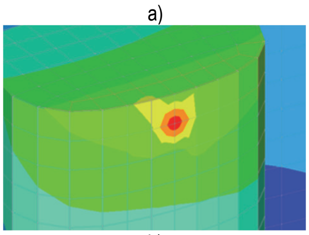
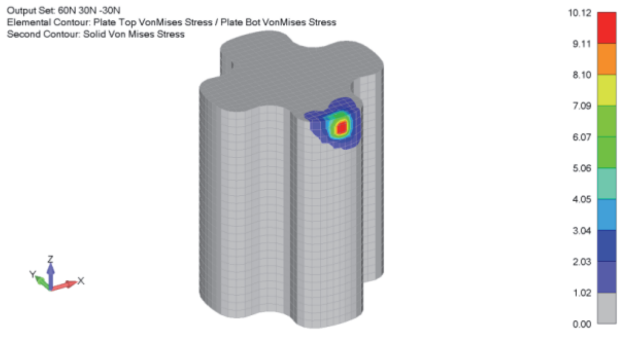


b)

Figure 8 a) Total displacements; b) Magnified detail of the workpiece on which the tool load acts during machining

The distribution of von Mises stresses in the volume of a deep pocket filled with a mixture of natrium silicate and fireclay flour is shown in Fig. 9. The distribution of stresses and deformations in the case of machining without a filled pocket with a mixture of natrium silicate and fireclay flour is shown in Fig. 10 and Fig. 11.



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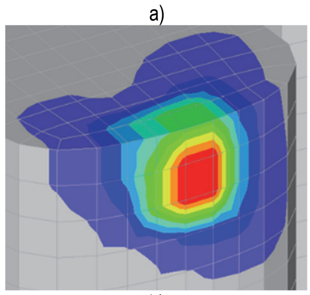
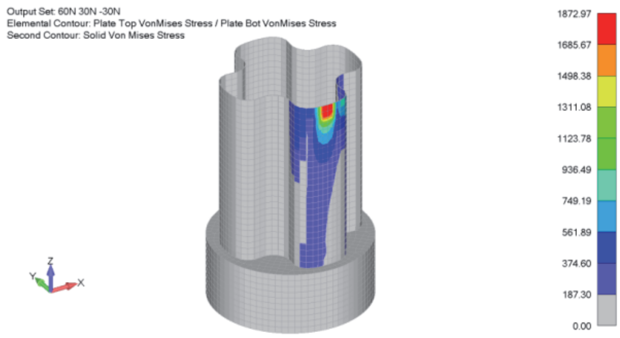


b)

Figure 9 a) Stress field - Whole model; b) Enlarged detail of the workpiece where the tool load is transferred through the thin wall



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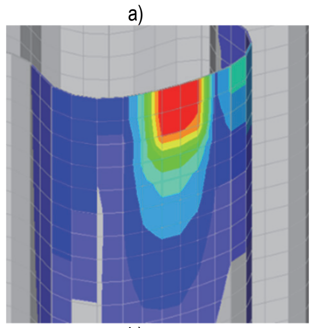
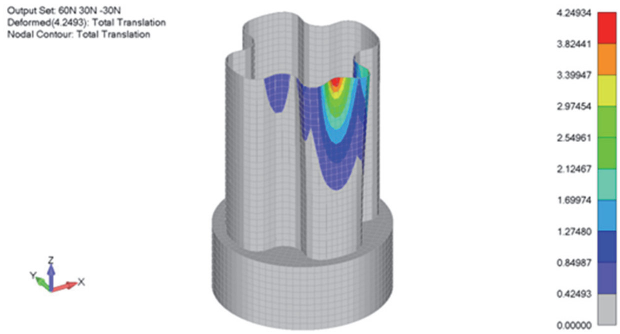


b)

Figure 10 Stress field in the case where the pocket is not filled with a mixture of natrium silicate and fireclay flour

The stress and displacement distributions shown in Fig. 7 and Fig. 8 show that the maximum stresses on the thin wall do not exceed the value of 50 MPa, while the displacements are less than 6 µm. Also, the display in Fig. 9 gives the distribution of the von Mises stress field in the volume of a deep pocket filled with a mixture of natrium silicate and fireclay flour. The maximum stresses on the contact surface of the mixture of natrium silicate and fireclay flour are only 10,12 MPa. In the case of machining a thin wall along the outer contour without filling the pocket with a mixture of fireclay flour and natrium silicate, which is only considered hypothetically, the stresses would exceed the value of 1800 MPa, while the displacements would be greater than 4 mm (Fig. 10 and Fig. 11).



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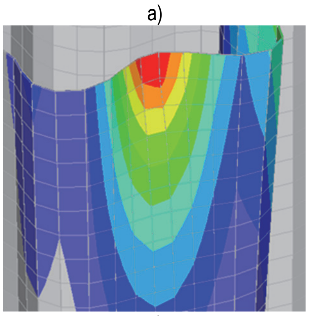

b)

Figure 11 Displacement field in the case where the pocket is not filled with a mixture of natrium silicate and fireclay flour

5 VERIFICATION

Verification of the proposed method of locating and clamping the thin-wall workpiece (Fig. 12) of aluminum AlMgSi1 was performed for the example of machining a deep pocket.

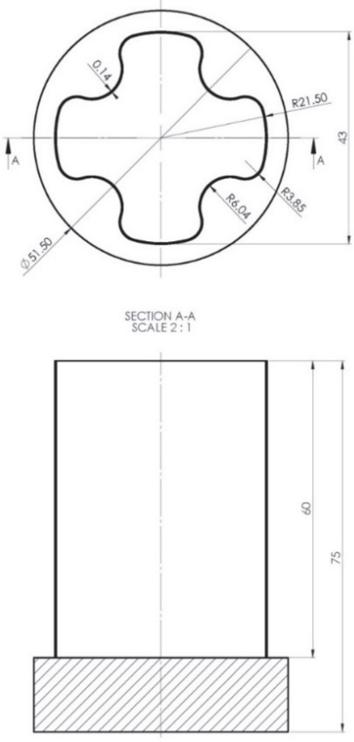

Figure 12 Workpiece

Machining was performed on a CNC milling machine HAAS VF1. The depth of the pocket was 60mm, and the tool is a flat spiral milling cutter with a diameter of 8mm with 4 cutting edges.

Fig. 13a shows a photo of the finished workpiece (pocket), while Fig. 13b shows a photo of the final process of decomposition of the mixture of natrium silicate and fireclay flour with water.

a)

b)

Figure 13 Photographic representation of the manufactured workpiece (pocket) and the final process of decomposition of the mixture of natrium silicate and fireclay flour with water after the completion of the machining process

After finishing the machining, the measurement was performed (Fig. 14). The measurement was conducted on a Coordinate measuring machine (CMM) Contura G2 by Carl Zeiss (maximum permissible error $MPE = (1,8 + L/300)$ µm, where L is the measured length expressed in mm). The basic measurements were carried out using a contact measuring styli with 1 mm diameter in a measurement laboratory with controlled microclimate conditions (20 ± 0,5) ºC. The measurement was performed using a 3D scanning strategy for the inner and outer shell with a point distance of 0,1 mm. A total of 20000 points were obtained for both the inner and outer geometry of the part. The base of the part was measured using the helicoid measurement strategy.

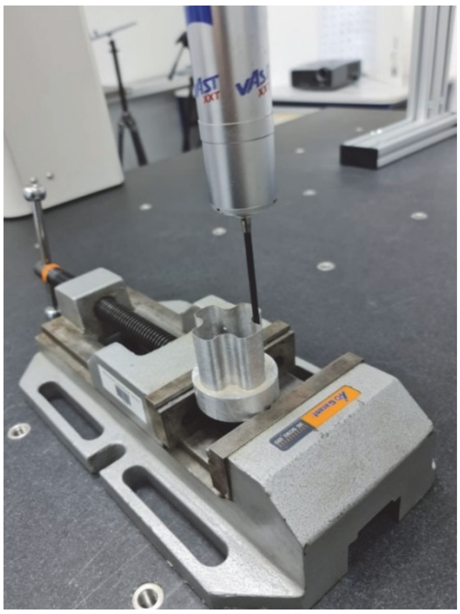

Figure 14 Measurement process

The results of the pocket depth and wall thickness measurements are shown in Tab. 1.

Table 1 Measurement results

	Pocketdepth h / mm	Wallthickness δ / mm
Minimum value	59,919	0,132
Maximum value	60,129	0,148
Mean value	60,052	0,144
Standard deviation	0,058	0,004

The performed measurements indicate a small dispersion of the results and the possibility of achieving the required dimensions within very narrow limits. The mean value of the pocket depth is 60,052 ± 0,058 mm and the mean value of the wall thickness is 0,144 ± 0,004 mm. The ratio of the mean values of the pocket depth and wall thickness is $h/\delta = 417$. This relationship indicates the possibility of the practical application of natrium silicate as a phase-change material in the fixture design for machining thin-wall workpieces of complex geometry.

6 CONCLUSIONS

The method of machining deep pockets with a large ratio of height to wall thickness using natrium silicate gives excellent results in terms of rigidity in the machining process, obtained machining quality, and dimensional accuracy of the finished workpiece. This material is commercially available, the technology of its application is simpler and can be significantly improved, and the cost is significantly lower. This proposed material enables the development of completely new technologies for the production of thin-wall workpieces. Existing technologies for the production of thin-wall workpieces are based on the application of classic complex systems or the application of existing lower performance phase-change materials.

The mixture of natrium silicate and fireclay flour greatly increases the rigidity of the workpiece by increasing the moment of inertia and practically excludes the problems of deformation of the thin-walls of the workpiece. The strong adhesion between the natrium silicate and the thin-wall aluminum workpiece also contributes to this.

The designed, implemented, and confirmed solution method of the fixture resulted from theoretical considerations related to the analysis of stress and deformation fields, FEM analysis, and the results of experimental tests of the bearing capacity of the connection formed between natrium silicate and aluminum as a metal material, that is, a thin-wall workpiece of complex shape machining.

On the basis of what was presented in the paper, the authors believe that the proposed method of machining workpieces with a large ratio of the height of the pocket in relation to the thickness of the wall showed high stability and reliability and great possibilities for increasing the level of productivity while meeting the required quality of the machining surface. Therefore, the assumptions and expectations were justified. This method also enables further development of current issues related to the field of research into the machining of thin-wall workpieces. The proposed method opens up many possibilities of theoretical and experimental research in the field of optimizing the technology of making deep pockets, choosing tools and optimizing the parameters of the machining mode from the aspect of achieving the maximum possible productivity and achieving the required machining quality.

Current use is limited to pieces with closed edges, although it is possible to additionally support the open edges with an auxiliary part to give a closed contour into which a mixture of natrium silicate and fireclay flour can be poured. Also the drying time of the mentioned mixture plays an important role. This time can be reduced by heating and also could be shortened by adding certain additives.

One of the key directions of the authors' future research will be directed towards the improvement, acceleration, and optimization of the process of hardening and decomposition of the mixture of natrium silicate and fireclay flour. The research will be focused on the analysis of the effects of using catalysts to speed up the process, determining the optimal temperature and time of heating the mixture, as well as the use of water under pressure for rapid decomposition of the mixture. The ultimate objective is to apply the proposed technology not only in the conditions of individual and small-scale production but also much more broadly.

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