DESIGN AND FEM STATIC ANALYSIS OF AN INSTRUMENT FOR SURFACE PLASTIC DEFORMATION OF NON-PLANAR FUNCTIONAL SURFACES OF MACHINE PARTS

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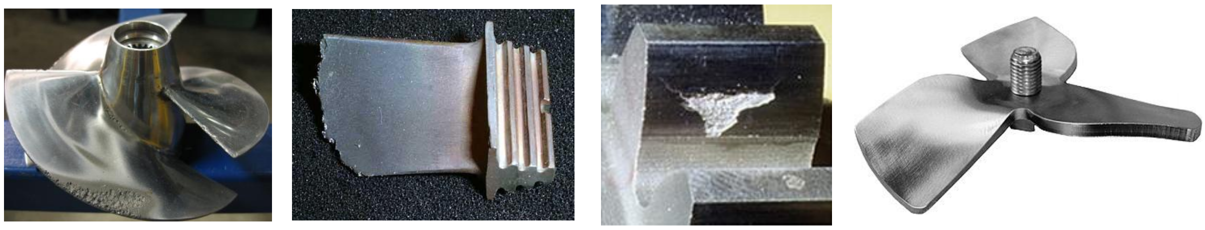
Abstract: *The paper presents the design of a specialized instrument for formation different types of regular microshape roughness on functional surfaces of parts with non-planar macroshape by using the process, called "surface plastic deformation". The elements of which it is constructed are explained and the results from carried out strength and deformation analysis, obtained by Finite Element Method, conducted using the Simulation module of the SolidWorks are also represented. On this basis some advantages and limitations of some of the surface plastic deformation process technological parameters are identified and recommendations for its implementation are given.*

Key words: surface plastic deformation process, regular microshape roughness, FEM analysis, SolidWorks.

1. INTRODUCTION

In many modern machines, aggregates and mechanisms, the most important structural elements have relatively complex shape (like those, shown on Figure 1, a÷d), and they often work in aggressive environments or under poor operating conditions. As examples may be indicated different types of propellers, turbine blades, spur or bevel gears, worm shafts, etc. Common to them all is that their performance depends mainly on the surface shape, the material from which they are made, and from the quality parameters of the contacting surfaces - texture roughness, residual stresses in the surface layer and the hardness [1,2,5].

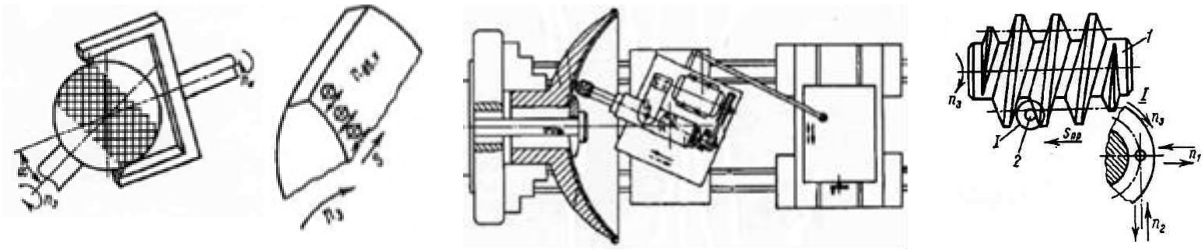
In the technological practice there are many examples which demonstrate that regular microshape roughness, obtained by the method of vibratory surface plastic deformation (VSPD) both for flat and cylindrical surfaces of different machine parts can optimize their parameters of contact significantly [4,5]. This method is based on plastic deformation (in not heated state) of the surface layer of the workpiece by pressing the hard steel ball (for example a ball from rolling-element bearing) with certain external force, that moves along to complex toolpath trajectory. As a result, specific overlays of traces from the ball are obtained and certain hills and dales are formed onto threated surface of the part, which size and form depends on the regime parameters of the VSPD process. Processing with this method increases the hardness of the surface layer of these machine parts and compressive residual stresses are formed therein, which further enhances some operating characteristics, such as increased strength, higher fatigue life, higher corrosion resistance, etc.



a) b) c) d)

Fig. 1. Machine parts with non-planar surfaces, usually working in under poor operating conditions: a) boat propeller damaged from cavitation; b) destructed turbine blade; c) surface gear failure – pitting; d) turbine propeller for chemicals or aggressive liquids.

The literature sources [4,5] shows that a variety of different kinematic schemes of the process VSPD have been developed till now, both for planar and cylindrical surfaces, and also for some non-planar surfaces from different types of parts, such as spherical, involute, helical and etc., of the type shown in Figure 2, a, b, c, d.



a) b) c) d)

Fig. 2. *Kinematic schemes of the process VSPD [5]: a) external spherical surface ; b)involute side surface from spur gear; c) internal spherical surface ; d)helical surface from worm shaft.*

However, there are some significant drawbacks of these classical kinematic schemes of the VSPD process, which are as follows:

a) Constructive embedded kinematics of manually controlled machine tools are usually insufficient for obtaining the needed complex trajectory of movement of the ball tool in VSPD. This necessitates to use additional eccentrically working mechanisms and devices (like the one shown on Figure 2, c for example) to provide the necessary oscillating movement of the ball tool, which increases the production costs to provide the technological equipment needed for implementation of this finishing method;

b) Speeds and feeds of the manually operated metalworking machines cannot be controlled uninterruptedly, which leads to restrictions in the achieved shapes and dimensions of the cells of the regular microshape. Moreover, the lack of synchronization between spindle and feed movements in majority of milling manually operated machines and the oscillating movement of the additional required devices often leads to distortion of the shape and size of the cells and to no uniformly distributed traces onto processed surface;

c) To avoid improperly crossing of the toolpath, and thus obtain heterogeneous relief, kinematic schemes for processing by VSPD on manually operated metalworking machines usually require interruption of contact between the ball tool and the machined surface [7].

This often leads to shock loads and therefore produces deterioration of the roughness parameters of the relief and to inhomogeneity of the resulting cells (by shape and dimensions);

d) Relatively low speed of the feeding movements of manually operated metalworking machines, combined with the need to break the contact between the ball element and the surface of workpiece, substantially increases operational time and thus this method is characterized by low productivity when processing larger parts.

Due to these reasons, the regular reliefs obtained by the VSPD method, described above, are still not widely used in modern machine-building manufacturing, and their implementation is most often limited to threating some functional surfaces of specific machine parts in terms of single item /one off/ type of the productions.

Obtaining regular reliefs by VSPD method is also possible if appropriate CAD/CAM system(s) and contemporary CNC machines are used instead manually operated machine tools. The described above disadvantages and limitations of the traditional approaches for VSPD can be considerably minimized and some of them can be completely avoided. Due to these advantages, at the Technical University of Varna two new kinematical schemes have been developed for formation of the regular microshape using none vibratory surface plastic deformation (i.e. SPD) process for planar and cylindrical surfaces, based on the capabilities of CNC machine tools [8]. Here, the ball tool again follows needed complex trajectories (as well as in VSPD process), but the toolpath generates using a mathematical model(s), which subsequently converted by CAM into corresponding NC program for CNC machine tool. This way the toolpath does not depend on the momentary combination of the kinematical parameters of the process, as is the case when using manually operated machines. For this purpose, specialized roller ball tool was designed and built for processing by SPD of flat and cylindrical external surfaces of workpieces, that can operate with the respective configurations of CNC machines (such as 3 and 4-axis vertical and horizontal milling centers) [8]. Its design, however, is not very suitable for the treatment of surfaces having shapes of the types, like shown in Figures 1 and 2, because its tip length is too short and has quite large diameter, determined by the larger diameters of the balls (for example 14 and 21 mm), with which it was originally designed to work. These peculiarities do not allow to use it in multiaxis schemes for processing by SPD, as it even at very small curvatures of the treated surface, occurs risk of contact with the non-working parts of the tool, which could lead to distortions in the resulting regular microshape. Therefore, it is necessary to redesign the existing instrument, so that it can work with a smaller diameter balls (of about 8 mm and smaller), and also its tip to be more elongated and with possible small diameter, in order to process the surfaces with the largest possible curvature. In addition, it is necessary to provide the possibilities of measuring the compression force of the tool’s roller ball element and possibilities to monitoring the changes, which may be occurs during the implementation of the SPD processing.

2. DESIGN AND OPERATION PRINCIPLE OF THE TOOL FOR MULTIAXIS SPD

The assembly of the redesigned tool for SPD is shown in Figure 3, a). It consists of a main tool body (pos. 1), which through straight shank (Ø32к6) fits in standard tool holders for milling spindles (type ISO 40), which have standardized round taper shanks according to DIN 2080 or DIN 69871 (see Figure 3, b). The outer diameter of the tool body (pos.1) has a metric thread M60h2 on which are mounted the rear nut (pos. 12) and the front nut (pos. 2). At the rear inner part of the body (pos. 1) is located the rear spring flange guide bushing (pos. 8). Around its periphery three threaded pins M12 (pos. 9) are mounted radially at an angle of 120^0. They are guided by three longitudinal slots of the tool body (pos.1), and this way the rear bushing (pos. 8) can move in an axial direction. The rear spring flange guide bushing is in contact with the helical spring (pos. 10) also, through which it ensures elastic contact between the spherical roller element (pos. 4) and the treated surface, and the necessary compressive force. In the design of the tool has been used standard manufactured helical compression ground end spring (Hennlich, Czech Republic), which has an outer diameter of 48 mm and a length of 65 mm, made of spring wire (DIN 2076) with a diameter of 8 mm, providing maximum force up to 3200 N at maximum tense length of 48 mm. The helical spring (pos. 10) presses the front bushing (pos. 11) where the force sensor type FCM (pos. 7) is mounted. The front part of the force sensor (pos. 7) presses the head of the plunger (pos. 6), which through the bronze bushing (pos. 5) mounted at its front end, gives the force from the spring on the spherical rolling element (pos. 4). The rolling elements (made of high strength steel 100C6) usually be taken from damaged ball bearings. They have a high hardness (60÷65 HRC), and diameters between 6 and 8 mm. The conical flange bushing, consist of two assembled parts (pos. 13 and 14), connected by M22X1.5 threaded joint, has the function to lead the plunger 6 in its axial movement and not allow any radial clearance of the roller ball. For that purpose, the front bronze bushing (pos. 3) is interchangeable, according to the diameter of the used ball (6 or 8 mm). The lack of radial clearance is provided by the bronze bushing (pos. 3), which is assembled with M10X1 threaded joint and its internal diameter has exactly in alignment against the diameter of the ball used. When the ball is not in contact with the treated surface, the force from the tensioned spring is counterbalanced by the tool body (pos.1) of the instrument, as transmitted by the head of the plunger (pos. 6), through the

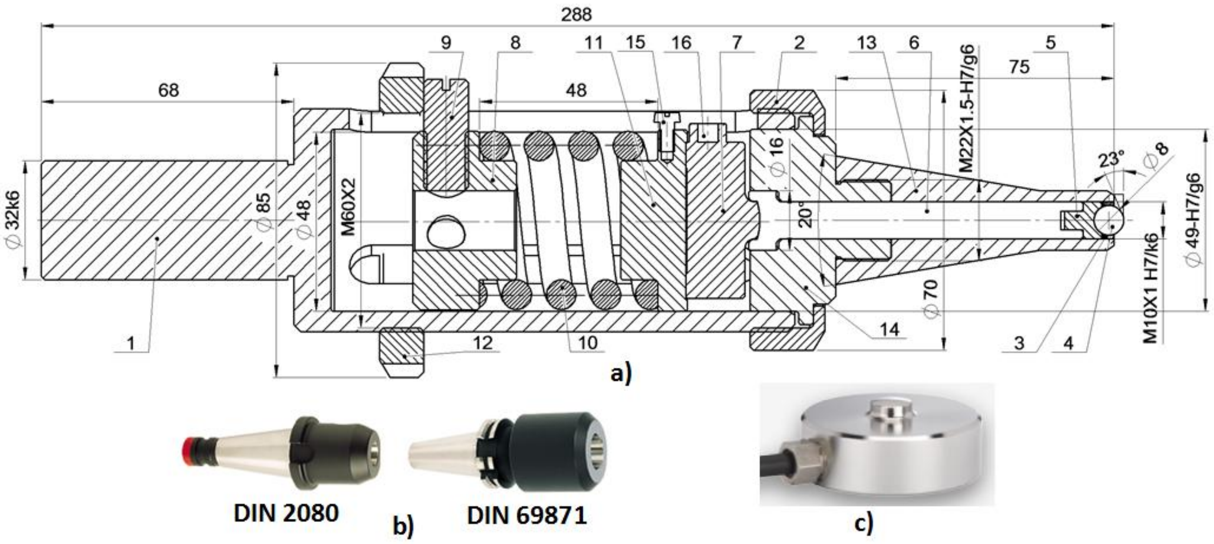


Fig. 3. a) Assembly of the redesigned tool for SPD; b) Tool holders type ISO 40, DIN 2080 and DIN 69871; c) Miniature force sensor type FCM (SIKA Dr. Siebert & Kühn GmbH & Co).

tapered bushing flanged (pos. 14), and by the front nut (pos. 2). Compressive force from the spring can be adjusted by turning the rear nut (pos. 12) and can be measured by miniature FCM force sensor (pos. 7) whose output connector (pos. 16) is directed and locked to one of the three axial grooves of the tool body (pos.1) by using the slotted cheese head screw M4 (ISO 1207) (pos. 15).

3. CONDUCTING FEM STRESS ANALYSIS OF THE TOOL BY SOLIDWORKS

Because the parts of the redesigned tool have a relatively complicated shape it would be difficult to use directly theoretical formulas from the Strength of Materials or Theory of machines, to determine the stresses and deformations in the design. Therefore, it is necessary to carry out a static analysis using FEM, and Simulation module of CAD-CAE system SolidWorks (SOLIDWORKS Corp., USA). The objectives of this analysis are to determine the maximum stresses and deformations and the minimal factor of safety of the construction of the above-described tool. All components of the device are made of steel grade 41Cr4 (BS EN 10083-1: 2006), with the exception of the parts (positions 3 and 5) from Figure 3, a), which are made of phosphor bronze RG5 (DIN 1705).

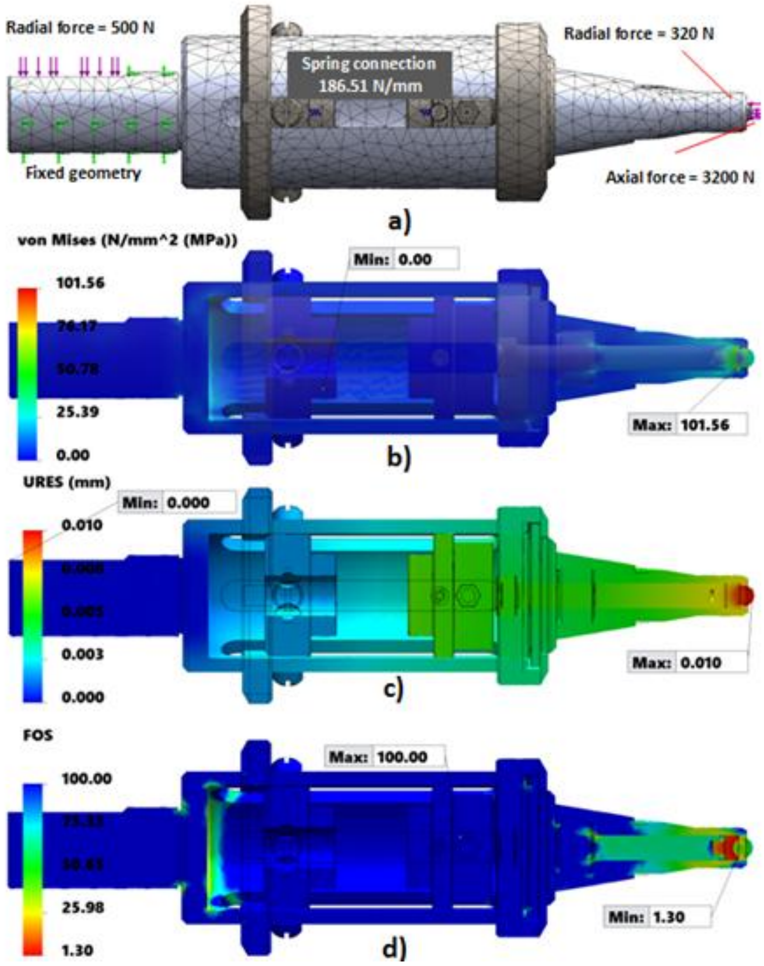


Fig. 4. a) Curvature based mesh of the tool's model, fixtures and external loads; b) VON-von Mises stress plot; c) URES-Resultant displacement plot; d) FOS–Factor of safety plot.

The sequence of steps to carry out the static analysis using the Simulation module of SolidWorks is as follows [3]:

1. Preliminary preparation of the tool's geometrical model in a convenient form for conducting analysis in SolidWorks: simplifies the model by excluding certain items (such as thread features, small holes and chamfers, the helical spring part model, etc.), that are not essential to the analysis.

2. Setting the connections, boundary conditions, fixtures and external loads (see Fig. 4a):

- Fixed geometry: rigidly fixed the cylindrical surface of the tool's straight shank;
- Setting a spring connector (compression only type) between rare and front spring's bushings with normal stiffness 186.51 N/mm, and 48 mm length at maximum possible deformation of the spring (these data were obtained experimentally);
- External loads: setting reactions of the load on the rolling ball, equal to 3200 N in axial and 320 N in a radial direction, as well as both forces from the tightening screws of the tool holder - 500 N.

3. Generating the finite elements mesh. Additionally, it is used control in order to generate finite elements with smaller dimensions in critical areas of the model. The number of nodes is 52085, and the number of the finite elements is 29291. Curvature based mesh is used, with Jacobian 16 points. The maximum element size is 7.36 mm, and the minimum element size is 1.47 mm.

4. Starting the simulation and after finishing calculations display the obtained results:

- **The maximum von Mises stress criterion** – see Figure 4, b). As can be seen from that figure, the maximum calculated stress is 101.56 MPa;
- **URES, maximal displacement (deformation)** - see Figure 4, c). The maximum calculated deformation is up to 0.010 mm for given dimensions and materials of the parts of the tool;
- **FOS (Factor of Safety)** – see Figure 4, d). The minimum calculated value of factor of safety of the design of the tool is 1.30, which is 30% higher than the minimum values for this ratio.

4. CONCLUSION

The results of the static analysis conducted by the finite element method using the Simulation module of SolidWorks, shows that the values of maximum stress, displacement, and the safety factor are within allowable limits. As can be seen from Figure 3, a) in these design parameters, the inclination angle between the axis of the tool and the curvature of treated surface can be up to 23 degrees without collision occurs. This will ensure trouble-free operation of the designed tool for processing of non-planar surfaces. Main advantages of the proposed constructive solution are relatively simplified design, including a minimum number of parts, and the ability to set up and continuously measuring the compression forces of the ball while rolling on the treated surface.

5. ACKNOWLEDGEMENT

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