NUMERICAL SIMULATIONS OF MECHANICAL PEENING OF TITANIUM ALLOY

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Abstract

Mechanical peening is based on striking a worked material surface by hard balls (shot).In this work, a pneumatic method, applied for double-sided shot peening of the worked sample surface, was selected. The samples were made of the titanium alloy WT3-1 (Ti-6Al-2Cr-2Mo).

The described work consists of two parts. The laboratory experiment was conducted in first part. After it realization, various observations were conducted. Observations of surface topography for samples were carried out before and after shot peening using scanning electron microscope (SEM). They revealed quite regular plastically deformed zones generated due to applied working. Neither microcracks, spallings nor delaminations in deformed surface layer of the titanium alloy were observed which attests to correct technological process of the surface hardening.

The numeric simulation of the peening process was conducted in part second. The physical model described non-simultaneous impact of three steel balls onto rectangular metal sheet made of the above-mentioned titanium alloy. Numerical FEM analysis for nonlinear dynamics (explicit) was carried out using LS-Dyna software (Livermore Software Technology Corporation). In the paper are presented maps of the material effort in surface layers for times corresponding to conditions after impacts of the first, second, and the third ball of cast steel shot.

Keywords: *surface layer forming, mechanical shot peening, impact, numerical simulation, finite element method*

1. Introduction

Technologies using burnishing and more and more popular mechanical peening can be ranked as the essential methods for mechanical working of surface layer forming. Mechanical peening is based on striking a worked material surface by steel, glass, or cast iron balls (shot). Shot is ejected by kinetic energy of a compressed air stream or a rotor (impeller) system (Fig. 1).

Impacting balls change plastic deformations, state of stress, and form topography of hardened material or element surface.

Layers generated by hardening are characterized by large specific compressive (positive) stresses. Research carried out by different authors [1, 2] show that 0.025 to 0.5 mm thick layers with specific stresses up to 800 MPa can be achieved. A change in yield point appears in those layers which are confirmed by over two-fold increase of measured hardness. This working is not expensive and does not need a sophisticated instrumentation and can be applied both for large and small surfaces. However it has some limitations. A process of generation of specified stresses is semi-quantitative and depends on metal surface coating. In general, peening intensity is homogeneous on the whole worked sample surface. Mechanical peening process produces high surface roughness, particularly in such soft metals as titanium and aluminum. That is why the surface layer of the worked element should be smoothed before being applied. Most frequently this rough layer is removed together with a major fraction of layer with specific stresses.

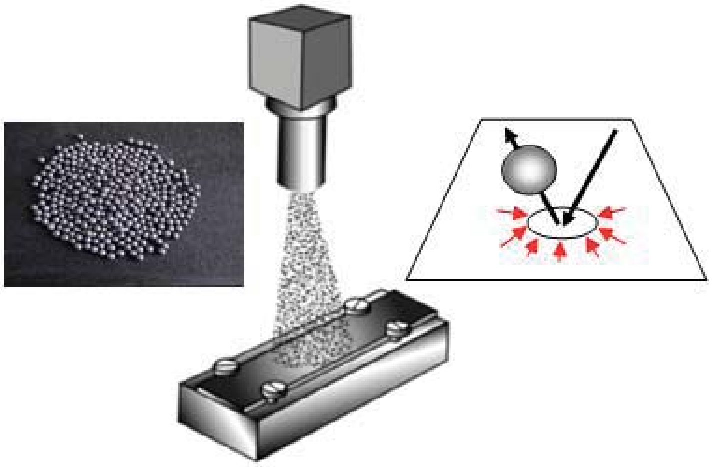


Fig. 1. Block diagram for mechanical shot peening using Almen testing plate

Numerical simulations using finite element method (FEM) are a good tool for intended design of specified properties of the surface layer of machine elements. The simulations are carried out in a few scientific centres in the world [5, 7, 9, 10] where modern software packages are applied, i.e. MSC.Nastran, LS-Dyna, MSC.Dytran etc. [8, 9].

2. Laboratory tests

2.1. Test methodology

A titanium alloy WT3-1 (Ti-6Al-2Cr-2Mo), typically used for machine elements, endoprostheses and so on, was selected as the essential material for tests.

Mechanical shot peening of the samples

A pneumatic method, applied for double-sided shot peening of the worked sample surface, was selected. Tests were carried out on the universal stand shown in Fig. 1, ensuring continuous circulation of shot between the chamber and the gun. For better measurement repeatability of the shot peening process special sample mounts were designed and manufactured. Surfaces not exposed to peening were shielded. During shot peening samples were rotated while the gun nozzle was fixed. In order to properly select process parameters a two-stage shot peening was suggested, each stage with shot of different granulation. Parameters for two-stage shot peening of sample made of the titanium alloy WT3-1 (Ti-6Al-2Cr-2Mo) are shown below.

Stage I

- cast steel shot SW 330 of diameter ϕ 0,8 mm and hardness 470 HV,
- distance between nozzle and worked surface L = 250 mm,
- nozzle diameter ϕ 5.3 mm,

- exposure time t = 60 s which ensured 100% covering,
- air pressure 0.45 MPa,
- peening intensity, determined on Almen testing plates, amounted to fA = 0.53 mm.

Stage II

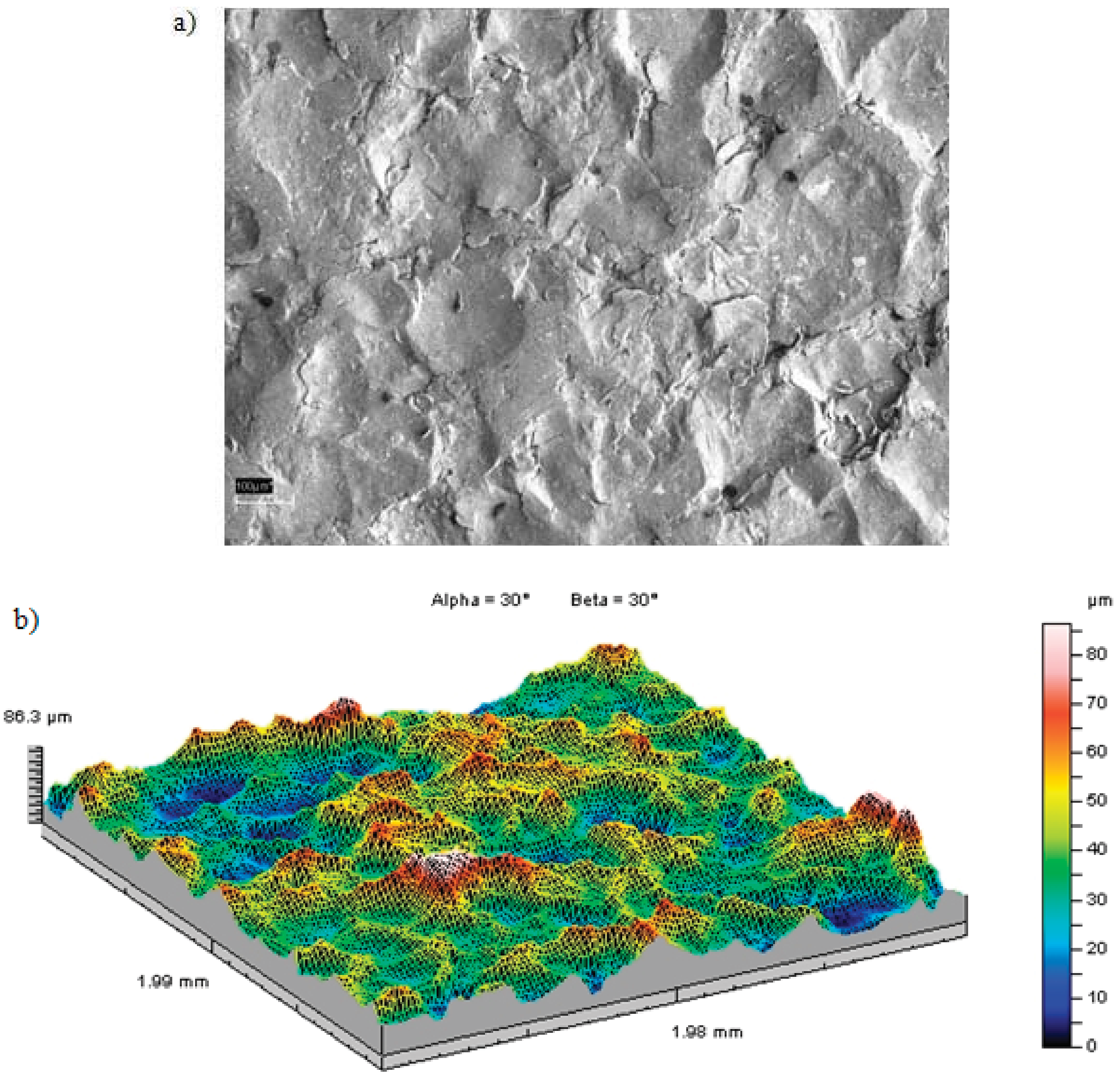
- cast stellite shot SW 170 of diameter ϕ 0.4 mm and hardness 470 HV,
- distance between nozzle and worked surface L = 250 mm,
- nozzle diameter ϕ 5.3 mm,
- exposure time t = 90 s which ensured 100% covering,
- air pressure 0.35 MPa,
- peening intensity, determined on Almen testing plates, amounted to fA = 0.39 mm.

Investigations of surface topography

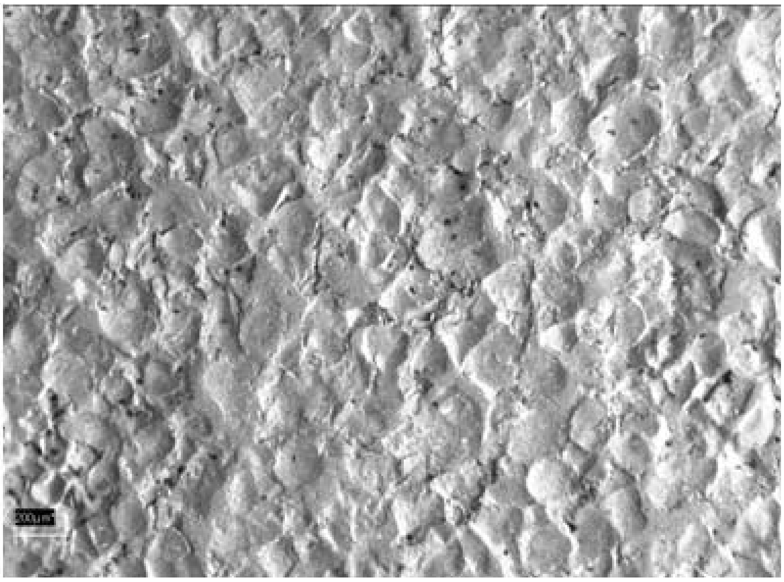
Tests of hardened surface included observations carried out with stereoscope and scanning electron microscopes (SEM) and analysis of surface topography using scanning profilometer.

2.2. Measurement results of surface topography

In result of the two-stage shot peening (I stage – high intensity process, II stage – medium intensity process) different surface topographies were registered and are presented in Fig. 2:



c)



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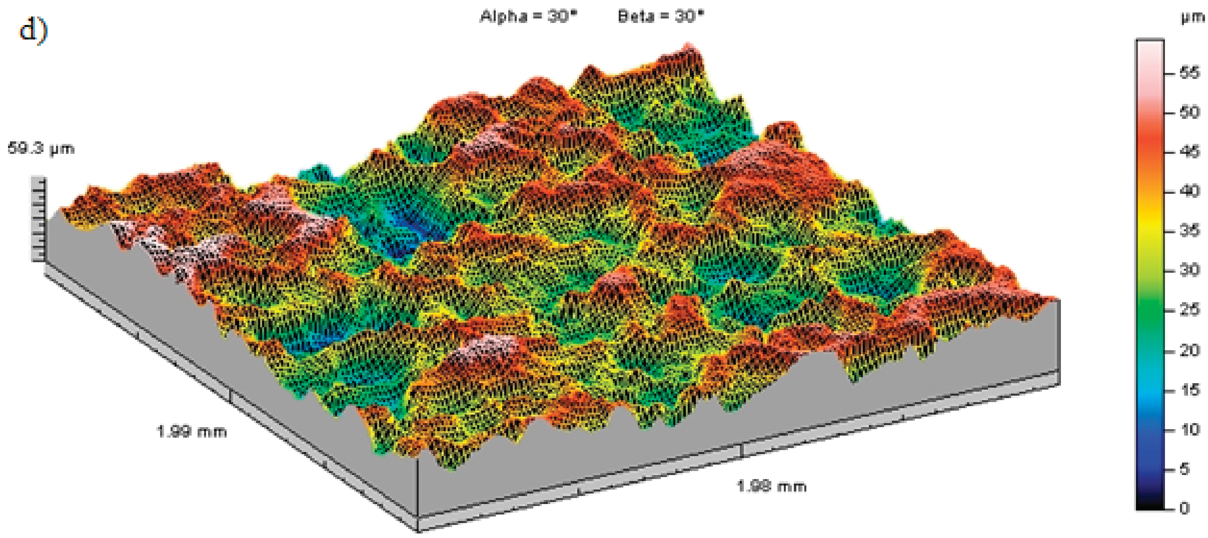

Fig. 2. Characteristic roughness profiles obtained from plane samples made of the titanium alloy WT3-1 (Ti-6Al-2Cr--2Mo): a, b) after mechanical shot peening – I stage (high intensity process – Ra ≈ 75 µm), c, d) – II stage (medium intensity process – Ra ≈ 50 µm)

As can be seen from 3-D profilograms, mechanical shot peening according to variant I increases roughness from 12 µm in the initial stage to 75 µm after shot peening while for variant II (lower peening intensity), carried out in order to lower surface irregularity, parameter Ra ≈ 50 µm was observed.

Observations of surface topography for samples made of the titanium alloy WT3-1 (Ti-6Al--2Cr-2Mo) were carried out before and after shot peening using scanning electron microscope (SEM). They revealed quite regular plastically deformed zones generated due to applied working. Characteristic zones hardened by local mechanical cold works are shown in Fig. 3. Neither microcracks, spallings, nor delaminations in deformed surface layer of the titanium alloy were observed which attests to correct technological process of the surface hardening.

3. Structure of the numerical model

After preliminary estimation of the shot peening process and literature analysis devoted to shot peening simulation [3-7] authors decided to neglect some less important phenomena accompanying shot peening. The authors paid attention mainly to process dynamics and mapping a shot contact with the processed material.

The physical model described non-simultaneous impact of three steel balls with radius $r = 1$ mm and velocity $v = 80$ m/s onto rectangular metal sheet made of the above-mentioned titanium alloy. The hardened titanium alloy sheet was place on a fixed and non-deformable plane.

Numerical model was described by a network of 5-, 6-, and 8-noddle solid elements. Material properties shown in Tab. 1 were assigned to each element. Elastic-plastic material model was used for description of material properties. The titanium alloy WT3-1 (Ti-6Al-2Cr-2Mo) sheet was implemented into the numerical model. Model geometry is presented in Fig. 4. A distance *a* between projections of ball centres onto burnished material surface was defined as an imprint diameter after simulation of the single ball imprint.

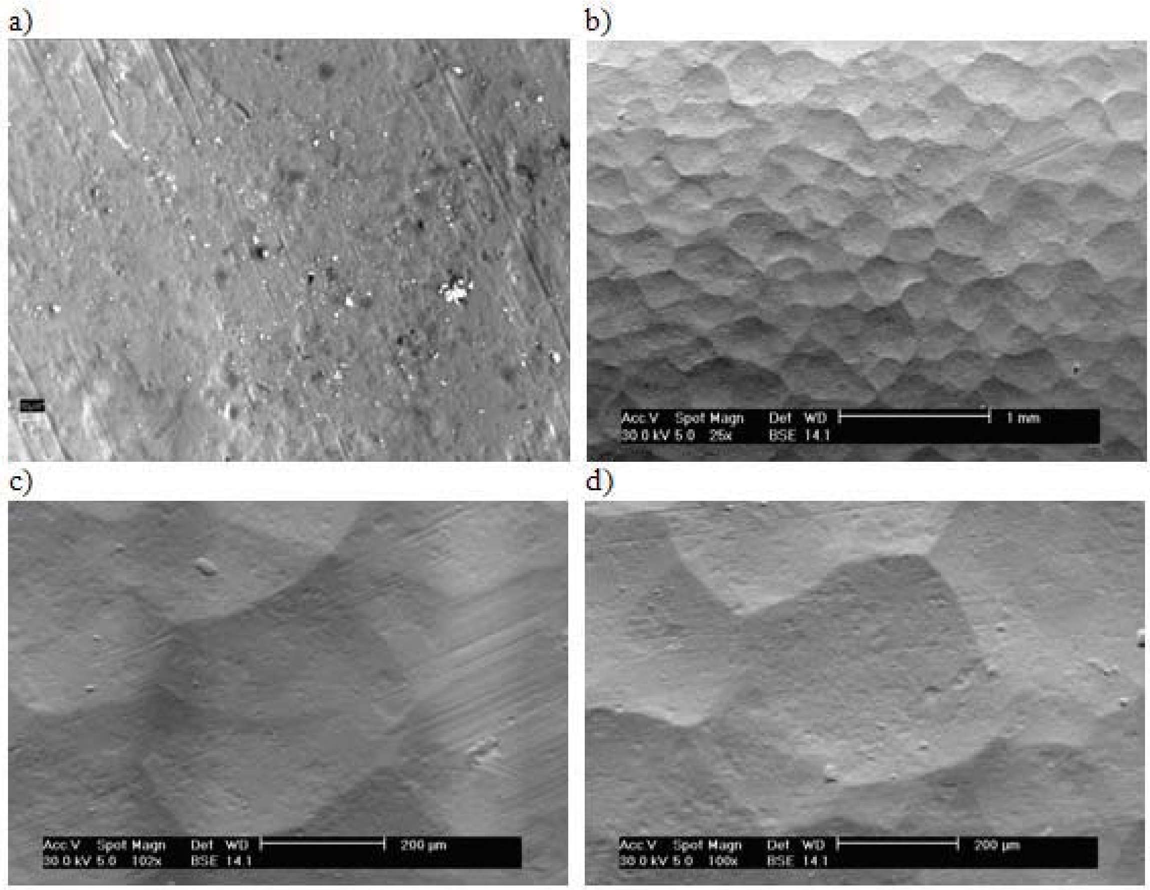

Fig. 3. A view of the characteristic surface topography zones of samples made of the titanium alloy WT3-1 (Ti-6Al--2Cr-2Mo) before and after shot peening: a) surface layer of the initial material before shot peening, b, c, d) surface layer of the material plastically deformed in result of the two-stage shot peening, scanning electron microscopy (SEM)

Material under shot peeling was placed on a rigid plane. The rigid plane was approximated in the simulation in the way that noddles positioned at the lower plane of freedom were deprived of motion in vertical direction (z). Lateral planes were fixed too – corresponding noddles were deprived of degrees of freedom in the direction perpendicular to these planes (x and y directions, respectively). A contact of the Eroding type was defined between elements of different material (ball – ball, ball – plane, and so on). For the Eroding type contact an automated deleting of these elements occurred if assumed criteria were fulfilled.

Numerical FEM analysis for nonlinear dynamics (explicit) was carried out using LS-Dyna software (Livermore Software Technology Corporation) [8, 9].

Tab. 1. Characteristic properties of the titanium alloy WT3-1 (Ti-6Al-2Cr-2Mo)

Parameters of the material	Parameter values	
	Shot	Ti-6Al-2Cr-2Mo
Young's modulus E, [GPa]	210	113.8
ultimate tensile strength R_m, [MPa]	1000	1200
yield stress $R_{e0.2}$, [MPa]	1200	860
tangent modulus E_T, [GPa]	2.1	1.1
Poisson ratio ν	0.3	0.32
density ρ, [kg/m^3]	8000	4540
hardening parameter B	1	1
friction factor μ	0.1	0.1

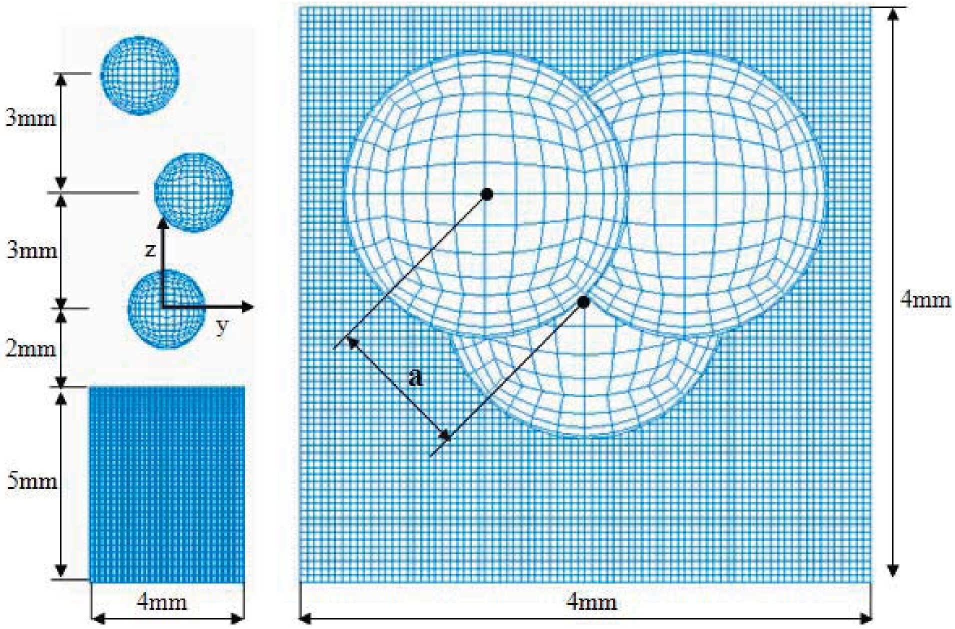

Fig. 4. Geometry of the numerical model

4. Simulation results

The first calculation was devoted to simulation of a single ball impact onto burnished material. The simulation was carried out to find a value of parameter a. Simulation results are presented in Fig. 5.

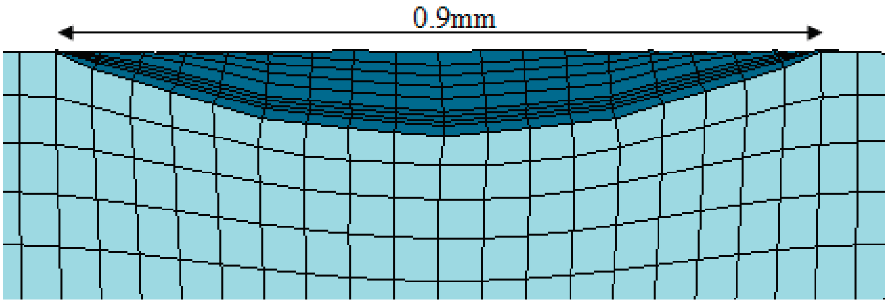

Fig. 5. A view of the plastically deformed zone generated in a process of mechanical interaction of a cast steel shot with surface layer of the titanium alloy WT3-1 (Ti-6Al-2Cr-2Mo)

Finally, for the simulation simplicity the value of a = 0.9 mm was taken.

Presented results show reduced stress distributions calculated according to Huber-Mises-Henckie energetic method (in units of Pa).

The maps properly demonstrate the state of the worked surface. The results are presented for t = 95 μs, i.e. immediately after reflection of the third cast steel ball (Fig. 6).

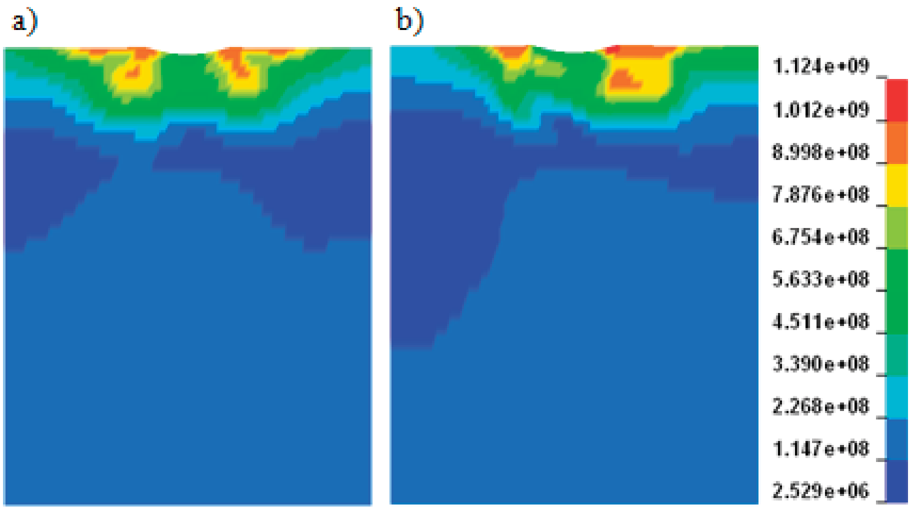

Fig. 6. Distributions of reduced stresses [Pa] for the C: a) – in the ZX plane, and b) in the ZY plane

In Fig. 7 are presented maps of the material effort in surface layers for times corresponding to conditions after impacts of the first, second, and the third ball of cast steel shot.

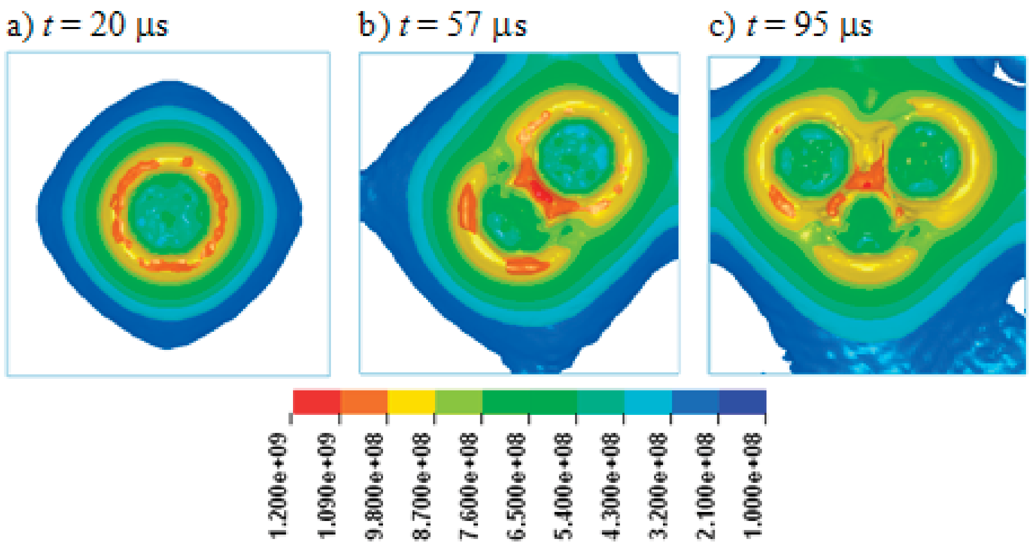

Fig. 7. Maps of the material effort [Pa] in a surface layer of the titanium alloy WT3-1 (Ti-6Al-2Cr-2Mo) after impact of: a) first ball, b) second ball, and c) third ball

5. Conclusions

After analysis of numerical calculations the following conclusions can be drawn:

- developed numerical models properly describe real plastic deformation processes of the titanium alloy WT3-1 (Ti-6Al-2Cr-2Mo),
- simulation of a complex shot peeling process was verified experimentally,
- applied material models (elastic-plastic model with amplification) describe material properties correctly,

- obtained calculation results, for example in form of stress maps or deformation maps, make precise observations of worked material condition in an individual process stage possible,
- introduction of some changes into developed FEM model gives a possibility to form desired properties of the worked material and improvement in working technology,
- advancement of the developed simulation needs expansion of the model with a huge number of randomly striking and mutually impacting cast steel shot balls,
- in the future numerical model a problem of description of mutually impacting balls should be solved as well as real boundary conditions (for example support points) should be included too because wave phenomena are clearly observed in the calculations.

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