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Finite Element Surface Layer Inheritable Condition Residual Stresses Model in Surface Plastic Deformation Processes

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Abstract. The residual stresses (RS) research and computational algorithms creation in complex types of loading on the product lifecycle stages relevance is shown. The RS forming finite element model at surface plastic deformation strengthening machining, including technological inheritance effect, is presented. A model feature is the production previous stages obtained transformation properties consideration, as well as these properties evolution during metal particles displacement through the deformation space in the present loading step.

Introduction

It’s known that the first kind residual stresses (RS) - one of important metal condition parameters, which largely determines machines critical parts and industrial constructions operational life. Especially RS great impact on the durability in different types of alternating loads, the RS value and parts section distribution have important role. In case of workpiece surface stress concentrator or initial crack appearance the compressive RS positive effect in the surface layer (SL) increases sharply and can give the several times parts durability increase [1].

The main condition for the first kind RS appearance is uneven over the workpiece cross section thermal or mechanical plastic deformation. However, due to the complexity of the parts power and thermal load processes in production and operation stages, accurate stresses calculation, acting in a particular part or parts of industrial construction, it is not always possible [2].

Most computational methods for stress-strain condition (SSC) determining is based on the large numbers of assumptions, idealizing computational schemes, loads and boundary conditions. It results to significant errors in the stresses evaluation, and in some cases makes impossible to obtain the theoretical solutions.

Such problem is becoming especially actual when you need to define RS in the product machining processes and their influence at subsequent operational stage processes. RS calculation methods at each machining stage has to consider surface layer complex nonmonotonic loading, metal plastic flow in DZ and deformation parameters technological inheritance (TI).

Theory

Among the machining methods high potential for generating in the SL of positive compressive RS are similar to the metal yield stress values have ways of finish-strengthening processing by surface plastic deformation (SPD) (Fig. 1) [3].

During SPD treatment in the deforming tool and workpiece contact area occurs asymmetrical deformation zone (DZ) ABCDEFG, limited contour lines front non-contact ABC (zone 1), front contact CD (zone 2), back contact DE (zone 3) and a rear non-contact EF (zone 4) surfaces and also FGA curve, describing the boundary of metal plastic flow zone [4]. Due to the stress and strain fields impact, metal particles are displaced in the area of wave along the some metal plastic flow lines, forming a workpiece SL (Fig. 1). The initial condition parameters, which the metal particles have before enter the deformation zone (line AG), are transformed into the accumulated on DZ exit (line GF).

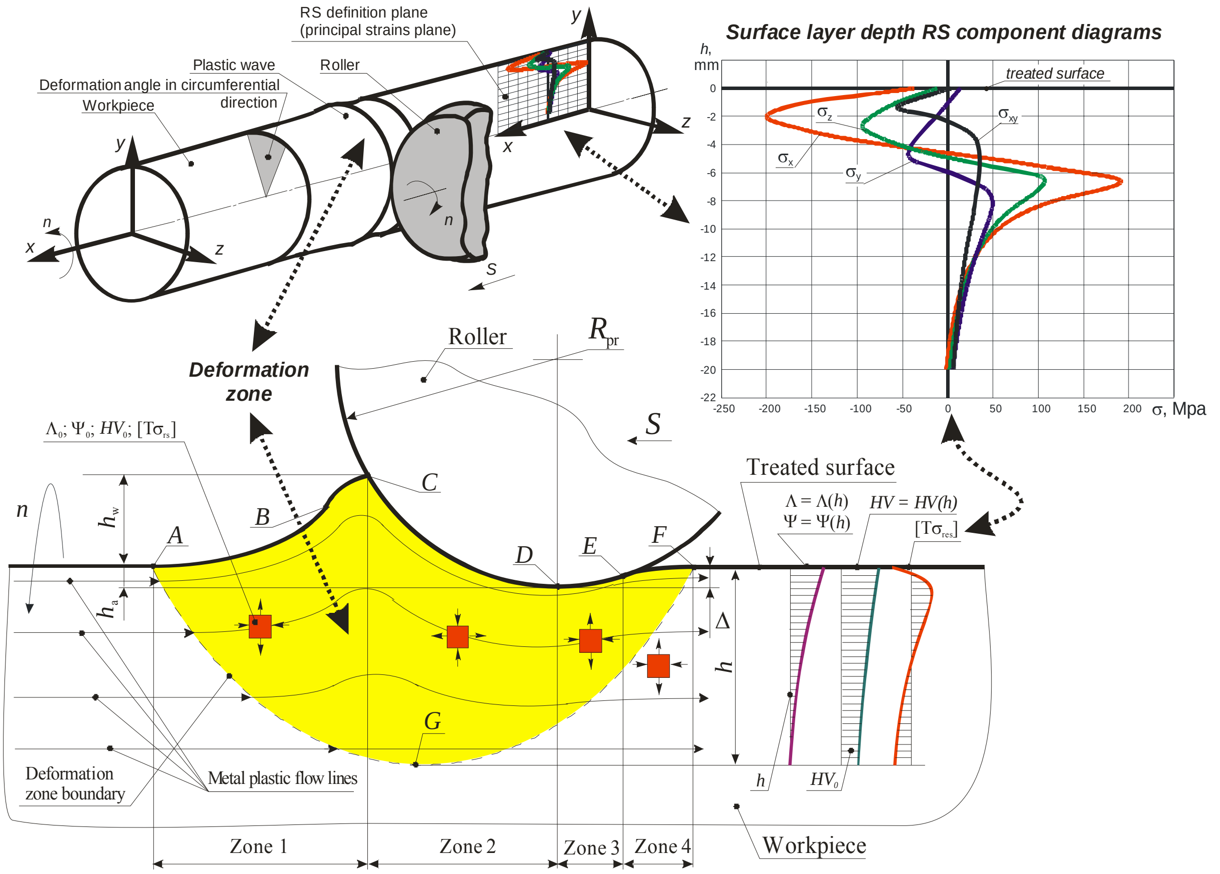

Fig. 1. Deformation zone scheme in the feed plane during processing SPD

Solution of the analytical RS determination after complex loading types taking into account TI effects is possible through device deformed body mechanics and methodology TI mechanics instruments in which:

- the SL condition formation and transformation in the machining stages and subsequent operational loading are considered as a uniform continuous process of strain accumulation, plasticity reserve exhaustion and RS transformation in surface layer metal. Thus, along with traditional quality parameters, for describing SL properties respectively using: the cumulative shear strain level Λ, the plasticity reserve exhaustion level Ψ and residual stresses components tensor $[T\sigma_{rs}]$ in coordinate system, associated with the workpiece or construction element form;
- the residual stresses formation and transformation in the manufacturing machining steps considered as complex non-monotonic metal loading result in DZ, in which the surface layer strain accumulation and metal plasticity reserve exhaustion occurs;
- the RS formation occurs in the metal mechanical properties changing due to plastic deformation conditions: loading history affects to the processes flow at every trajectory point inside DZ;

- final RS manifest themselves during the operation, transforming in each operating loading cycle; durability defines entire load prehistory.

As is known, RS tensor may be represented by the expression

$$[T\sigma_{rs}]=[T\sigma_{rep}]-[T\sigma_{iel}]+[T\sigma_{uwr}]+[T\sigma_{t}], \qquad (1)$$

where components are [5-6]:
$[T\sigma_{rep}]$ – stresses tensor, appearing in the real elastic-plastic body under loading;
$[T\sigma_{iel}]$ – stress tensor, which would occur in a ideal elastic body under identical loading;
$[T\sigma_{uwr}]$ – with unload elastic stresses tensor when workpiece releases;
$[T\sigma_{t}]$ – unload elastic thermal stresses tensor.

According to the TI mechanics instrument:

- at each machining step in DZ (as described above on SPD processing example) is a continuous strain accumulation and plasticity reserve exhaustion occurs, which leads to the surface layer formation with defined quality parameters: the hardening depth and degree, the roughness and the residual stress;
- in the operational fatigue loading, the strain accumulation and plasticity reserve exhaustion processes continue, flowing under continuous residual stresses relaxation. With the strain limit accumulation ($\Lambda = \Lambda_p$), there is a complete plasticity reserve exhaustion occurs ($\Psi = 1$). This condition corresponds to the first kind residual stress tensor relaxation to negligible values ($[T\sigma_{rs}] \approx 0$) and the fatigue crack appearance. A strain limit accumulation, a complete plasticity reserve exhaustion and fatigue crack nucleation occurs at a probable failure point, which may be located both on the surface and at some distance from it. The resulting stress condition determined by residual and external load stresses tensors. When the both constituents principal stresses vectors direction match and a fatigue stresses cycle is symmetrical, the workpiece (machine part) surface layer works in a cycle asymmetry condition all the more, than the residual stresses greater. The average cycle stress is equal to the residual stress, and the amplitude is equal to the external load stress. Under cyclic loading compressive residual stress increases and tensile - reduce fatigue life;
- at each machining or operation step the residual stress forming occurs under influence of:
  - the strain level, metal accumulated by metal at the current time;
  - the residual stresses, generated in the previous load step;
  - the mechanical and thermal stresses, generated during a load application in the present load step;
  - the unload elastic stresses, when the load is removed;
  - the stresses, additionally appearing when workpiece releases.

Hereditary SPD Process and Surface Layer Condition Parameters Forming Model

For a complete TI phenomenon account and its influence on the SL metal final properties formation necessary to create a theoretical model representations about the metal stress-strain condition is not only taking into account the properties transformation, obtained in previous production and operation stages, but also taking into account changes in these properties during the metal particles move through DZ space at the current load stage.

At the same time, if we consider the principal strains plane (Fig. 1), the feed direction tool and DZ displacement has a discrete character: next DZ appears with offset from the previous on the feed value, which upon SPD treatment usually varies between 0.05-0.3 mm/rotation.

In the early finite element (FE) SPD, cutting and dimensional joint running-in process models, proposed in [3, 7], said discrete not modeled on the one hand simplifies the model and subsequent calculations, on the other hand - it is a disadvantage.

In the previously proposed models, the workpiece upper boundary was obtained experimentally a deformation zone contour. The contact area with the roller was simulated as an arc, which is identical to the roller profile radius (Fig. 1). The model lower boundary was rigidly fixed at both axes, roller has a single offset along the x-axis with feed value S. This allowed to simulate the «instantaneous» stresses and strains values, that occur in DZ space.

A feature of this model is that the tool doesn't interact with the entire treated surface - simulated only SSC in DZ, whose geometry is obtained on the basis of experimental data. It's assumed that the metal particles pass through DZ and form a treated SL. Moving through DZ space along some flow-line, due to the stress and strain fields, metal particle has a complex non-monotonic loading. To calculate the accumulated mechanical condition parameters was used the hypothesis, that in the next load step, which occurs via 1 workpiece rotation, the particle, moving along the flow-line, changes its SSC on some new, located in DZ space from the previous along workpiece axis with offset on the feed value. Wherein it doesn't take into account that between these two conditions occurs unload, leading to an intermediate stress-strain condition appearance, and a next load step occurs in the metal properties conditions, have changed in the previous step.

In this paper, for SL metal hardening treatment by roller tool SPD was created the RS forming finite element model, taking into account inside DZ metal properties transformation and also integral metal mechanical condition parameters calculated. At the same time we made the following initial conditions and assumptions:

1. The occuring strain had only mechanical nature: the temperature component is not taken into account because of the metal small heating in the loading process.
2. Simulated isotropic material with the mechanical condition parameters corresponding to parameters of steel 45 (GOST 1050-88, hardness 160-180 HV) in the delivery state.
3. Flow curve linear approximation, taking into account the metal hardening (Fig. 2), is used. The following parameters were used for description:

- Young's modulus E, which characterizes the elastic section angle α;
- extrapolated yield stress σ_{eys}, corresponding to stresses axis segment, which is determined by the plastic flow line extension;
- Poisson's ratioν;
- tangential module T_{mod},, which characterizes the plastic flow line angle β.

4. In view of the relatively low error value, to simplify the calculations, don't include the Baushinger effect.
5. The workpiece releases unload elastic stresses tensors was adopted zero because a set of conditions, specified in [8] for the symmetric cylindrical workpiece treatment, was performed.
6. Appearing edge effects don't significantly affect the simulation results, because workpiece model was large enough compared to the appearing deformation zone.

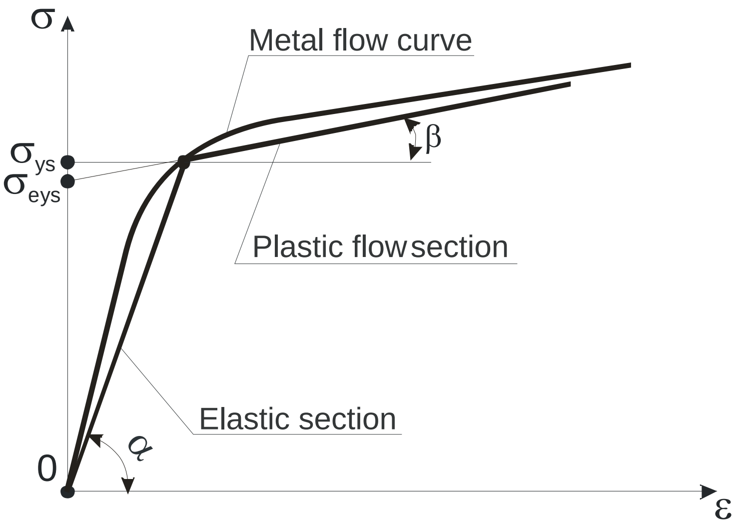

Fig. 2. Bilinear flow curve approximation diagram

The problem was solved in the plane-strain formulation. It is assumed that all deformation processes in DZ occurring in the principal strains plane, passing through the workpiece rotation axis (feed plane). This is confirmed by SPD processes research results, presented in [4], according to which:

- plastic wave height (ABC, Fig. 1) in the longitudinal direction is much larger than in a cross;
- feed plane largely corresponds to the main strain plane concept, since the rotation speed plane strain is less than a similar in feed plane.

Belonging to principal strains plane, treated cylindrical workpiece fragment of length L = 50 mm and height h = 20 mm was simulated (Fig. 3).

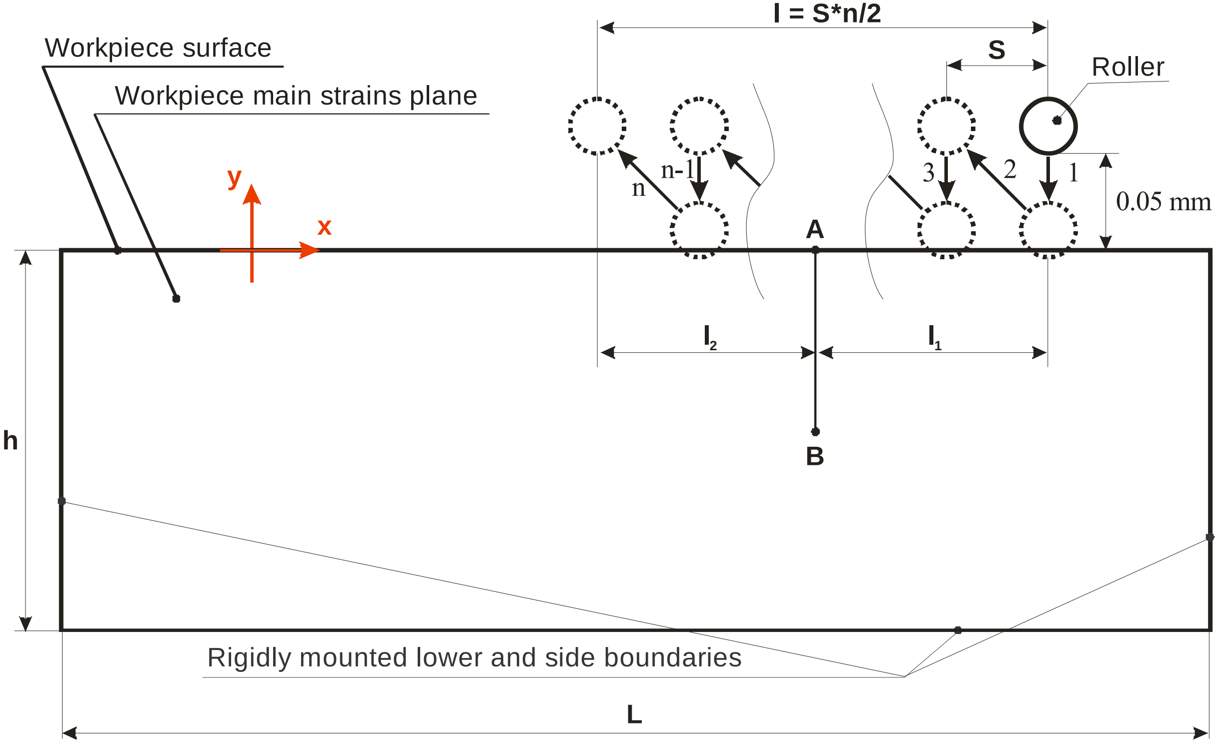

Fig. 3. SPD processing simulation problem statement scheme

The fragment lower and side boundaries rigidly fixed on both axes. Deforming roller simulated as an absolutely rigid body, having a determined profile radius arc.

This assumption is justified, because numerous researches have shown, that during the SPD treatment, in the surface interaction process:

- deforming tool has very small abrasion;
- any significant tool deformation is not fixed.

During the simulation, the selected SPD treatment settings located approximately in the middle of used ranges (Table 1).

Table 1. Simulated SPD treatment parameters settings

Parameter mode	Symbol	Measure unit	Simulation value	Parameters value range
Roller profile radius	R_{pr}	[mm]	5	1.6-16
Feed	S	[mm/rot]	0.1	0.05-0.25
Actual roller tightness	h_a	[mm]	0.05	up to 0.1 mm for steel 45

In the initial position the tool has clearance of 0.05 mm from the surface (Fig. 3).

On the first and any subsequent odd simulation step was performed loading - the surface direction tool displacement with the value of 0.1 mm. Thus, the tool being indented into the surface with the actual tightness value.

On the second and any subsequent even simulation step was performed unloading - the surface direction tool retraction with the value of 0.1 mm, while moving along the surface with the feed value. Thus, the tool again had a relative to the surface initial clearance.

A total 300 steps was simulated - 150 loading steps and 150 unloading steps. The treated surface length in the presented model was

$$l = S*n/2 = 15 \text{ mm}. \qquad (2)$$

The basic modeling idea of the stress-strain condition and residual stresses transformation in deformation zone is as follows. Certain modeled fragment section AB is positioned so, that at the first load step is not yet in the DZ space. At the same time at the penultimate load step this section has already left DZ space. In the feed direction distance l_1 (from the tool starting position to the section AB) was 5 mm, distance l_2 (from section AB until the end tool position) - 10 mm (Fig. 3-4).

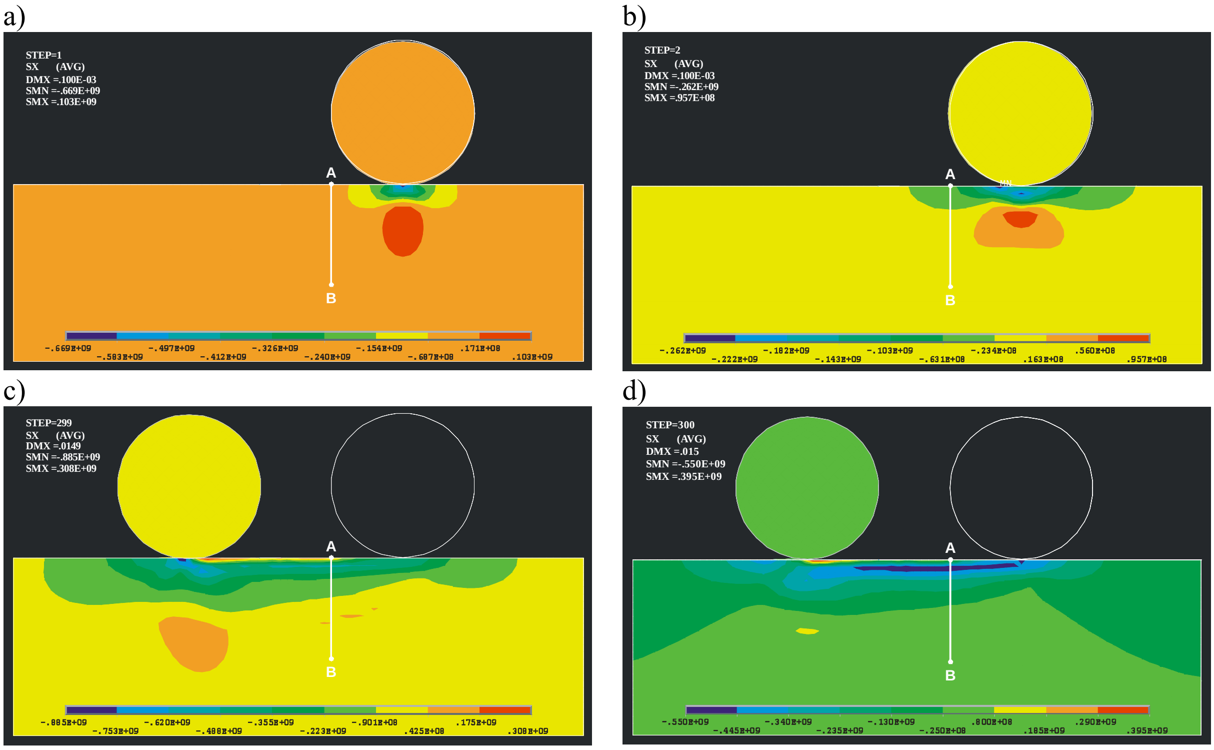

Fig. 4. The axial stresses distribution simulation after: a) 1-st step (loading); b) 2-nd step (unloading); c) 299-th step (loading); d) 300-th step (unloading)

As, in the all modeling steps implementation said section passes through a DZ space, this section is the treated SL depth trajectory, in which strain accumulation, partial plasticity reserve exhaustion and RS tensor forming based on changing the SL properties was happened. Fig. 4 is an example of the axial stresses distribution after the 1-st, 2-nd, 299-th and 300-th load steps (marked section in which SSC parameters at each simulation step are fixed).

For further mechanical condition parameters calculations, after the model solution receiving in a selected section AB for each simulation step was fixed the following parameters: the nodes coordinates, the nodes displacement vector components, the stress tensor components, the total elastic-plastic strain tensor components. The following also have been taken in the calculation:

- workpiece rotation frequency 300 rot./min, then, one workpiece rotation time is 0.2 s;

- the circumferential direction deformation angle (DZ space) 10° (taken from the data of [3-4]), then, one SL loading and unloading cycle time is 0.0054 s.

- half of this time (0.0027 s) loading occurs, and as many - SL unloading.

Results and Discussion

Mark some RS tensor SL depth distribution features (Fig. 5):

1. The largest compressive stress values (up to 560 MPa) has an axial component σ_x. These values are close to the hardened metal yield stress, which is favorable because of a significant influence of this component to the workpiece (machine part) cyclic durability during it operational (fatigue) loading. Compressive stresses σ_x on the surface and at a nearby layer, summed with the operating tensile stresses, cancel each other, thereby reducing the acting stress tensor.

These values correspond to the experimental data, obtained in [4], where the axial RS value at SPD reaches -800 MPa, and the circumferential RS (σ_z in Fig. 5) - up to -400 MPa.

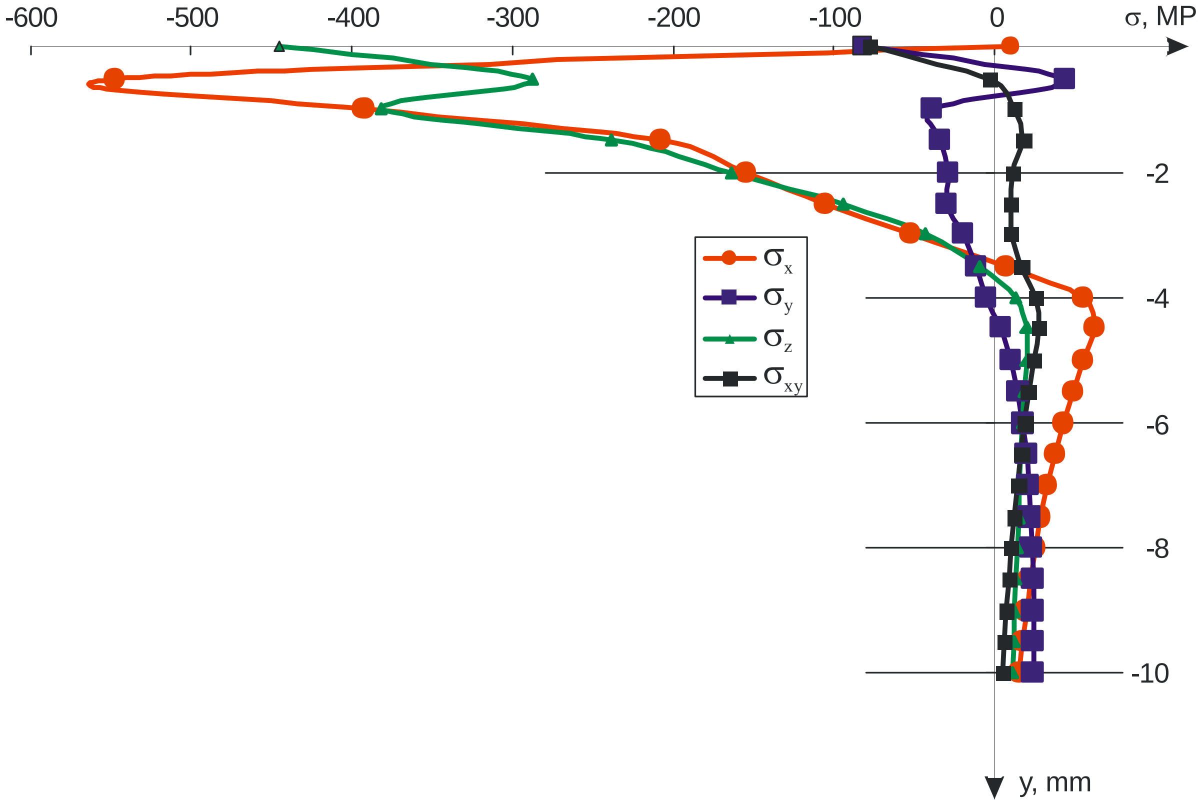

Fig. 5. The residual stress tensor components distribution in the surface layer depth after the 300-th simulation step (y = 0 mm corresponds to the workpiece surface)

2. The axial component detects the compressive stresses extremum, located at a depth of 0.5 mm below the workpiece surface. This is consistent with the results of [9], in which the author emphasizes the compressive RS extremum possibility on the workpiece surface, and at a certain depth.

3. The component σ_y (radial RS) has a considerably smaller values than σ_x and the same depth spread. On the surface and in the surface layer σ_y has a predominantly negative values not exceeding -100 MPa. It also has smaller differences as to the region of tensile and compressive values to. This corresponds to the results obtained in [4], according to which the SPD surface radial component has zero value. Wherein the author notes, that the characteristic SPD RS tensor small σ_y values are not significant disadvantage due to insignificant influence of this component to the workpiece cyclic durability.

4. The residual stresses depth distribution reaches up to 7 mm, wherein a significant residual stresses normal components compressive values depth distribution has obtained (up to h = 4 mm).

Overall, the picture is in agreement with the analytical and experimental results obtained by the previously published works authors.

Conclusion

1. The SPD finite element model, was developed. Its feature is the deforming tool with elastic-plastic half-space discrete (in principal strains plane) interaction nature accounting. Discrete interaction accounting achieved by the original scheme of multistep loading, unloading and new deforming tool feed displacement inside the deformation zone.

2. Within each «loading-unloading» cycle the simulation, metal stress-strain condition and residual stresses tensor calculation was performed

3. Each cycle loading and unloading history accounting allowed to estimate the TI phenomenon influence to the surface layer metal properties formation process. TI phenomenon influence estimation is available not only at the life cycle (treatment and operation) stages level, but also inside each stage by taking into account inside deformation zone metal properties changes.

4. The obtained residual stress tensor components numerical values reflect the metal properties formation hereditary nature inside the deformation zone during the surface plastic deformation process.

5. Obtained results allow to perform the subsequent accumulated SL metal mechanical condition parameters calculations, taking into account the TI phenomenon.

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