The Surface Layer Mechanical Condition and Residual Stress Forming Model in Surface Plastic Deformation Process with the Hardened Body Effect Consideration

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Abstract. The mechanical condition and residual stresses (RS) research and computational algorithms creation in complex types of loading on the product lifecycle stages relevance is shown. The mechanical state and 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 is known that the mechanical condition, such as deformation degree and first kind residual stresses (RS) - one of important metal condition parameters, which largely determines product operational life, especially in different types of alternating loads [1].

However, accurate stress-strain calculation, acting in a particular part of the workpiece, it is not always possible, most of the computational methods and algorithms, as a rule, cover only simple (one-, two-axle) loading types and don’t allow to perform calculations in the complex power and thermal loading types, taking place in manufacturing and operation stages processes [2].

Along with it, the technological inheritance (TI) phenomenon significantly affects to the mechanical condition formation and transformation, because the workpiece stress-strain condition (SSC), obtained at the previous loading stages, influence to the flow of the processes at each subsequent stage.

Theory
Among the machining methods high potential for operational life increase by generating in the surface layer (SL) hardening effect and favorable compressive RS are similar to the metal yield stress values have surface plastic deformation (SPD) finishing-hardening treatment methods (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. 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).

Solution of the deformation and RS analytical determination after complex loading types, including SPD treatment, taking into account TI effects is possible through the technological inheritance mechanics instruments, in which [3-5]:

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- the SL mechanical 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, resulting complex non-monotonic metal loading in the DZ. Thus, along with traditional quality parameters, for describing SL properties respectively using: the cumulative shear strain level (CSSL) $\Lambda$, the plasticity reserve exhaustion level (PREL) $\Psi$ and residual stresses components tensor $[T\sigma_{rs}]$ in coordinate system, associated with the workpiece or construction element form;
- the mechanical condition and RS formation occurs in the metal mechanical properties conditions changing due to plastic deformation: loading history affects to the processes flow at every trajectory point inside DZ;
- final mechanical condition and RS manifest themselves during the operation, transforming in each operating loading cycle; durability defines entire load prehistory.
- 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 ($\Lambda = \Lambda_f$), there is a complete plasticity reserve exhaustion occurs ($\Psi = 1$). This condition corresponds to the first kind residual stress tensor relaxation to negligible values ($[T\sigma_{ocm}] \approx 0$) 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. Under cyclic loading compressive residual stress increases and tensile - reduce fatigue life.
Thus, for a complete TI phenomenon account and its influence on the SL metal final properties formation necessary to create a 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.

To solve this problem the RS formation at roller tool SPD hardening SL treatment finite element model was created, taking into account inside DZ metal properties transformation.

During the modeling the following initial conditions and assumptions was taken:

1. 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.
2. The occurring strain had only mechanical nature due to the small metal heating in the loading process.
3. Flow curve linear approximation, taking into account the metal hardening, is used.
4. In view of the relatively low error value, to simplify the calculations, the Baushinger effect were not taken into account.
5. The workpiece releases unload elastic stresses tensors was adopted zero because a set of conditions, specified in [6] for SPD treatment, was performed, and also because workpiece model was large enough compared to the appearing deformation zone geometrical dimensions.
6. The plane-stress formulation was used, during which the strain accumulation, plasticity reserve exhaustion and RS formation processes was modeled in the feed plane, passing through the workpiece rotation axis. According to [7], since the plastic wave height and, accordingly, the strain values in the longitudinal direction much larger than in the cross, from a mechanical point of view, feed plane better suits the principal strains plane concept.

As the treated surface cylindrical workpiece fragment of length L = 50 mm and height h = 20 mm was simulated (fig. 2). The fragment lower and side boundaries rigidly fixed on both axes. Stress-strain state zone size, which occurs in the processing, is much less enough than the simulated fragment, therefore, the edge effects, Appearing in this formulation, make the simulation results very small error.

Deforming indenter simulated as an absolutely rigid body and was represented by a circle with a determined profile radius arc. This assumption is valid, because numerous researches have shown, that during the SPD treatment, deforming tool has very small abrasion, thus any significant tool deformation is not fixed.

At the same time, if we consider the principal strains plane (fig. 1-2), the DZ displacement in tool feed direction has a discrete character: next DZ appears with the feed value offset from the previous, which upon SPD treatment usually varies between 0.05-0.3 mm/rotation.

This circumstance accounting is a model novelty. So in the early finite element SPD cutting and dimensional joint running-in process models, proposed in [4-5, 8], said discrete not modeled, that on the one hand simplifies the model and subsequent calculations, on the other hand - it is a disadvantage.

In the initial position the tool has some clearance from the surface (fig. 3).

On the first and any subsequent odd simulation step was performed loading - the surface direction tool displacement with the same value, presupposing indentation into the surface with the specified tightness value.

On the second and any subsequent even simulation step was performed unloading - the surface direction tool retraction to the initial distance, with its simultaneous displacement along the surface with the feed value.

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 mm.

The basic modeling idea is that, the 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 l1 from the tool starting position to the section AB was 5 mm, distance l2 from section AB until the end tool position - 10 mm (fig. 2-3).
Thus, 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. 3 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.

After solving the model in the selected section AB for each simulation step the following values were fixed: node coordinates, nodes vector displacement components, stress tensor components, elastic, plastic and total elastic-plastic strain tensor components.

For further mechanical condition parameters calculations according to [3, 7] the circumferential direction deformation angle was taken to be 100. Workpiece rotation frequency is taken equal to 300 rpm.

Thus, one workpiece rotation time is 0.2 s. Because taken deformation (DZ space) in circumferential direction is 100, cycle time, in which SL loading and unloading occurs, is 0.0054 s. It was taken, that half of this time (0.0027 s) loading occurs, and as many - SL unloading.
Fig. 3. 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)

According to taken assumptions, as the workpiece SL loading and unloading, accompanied by strain accumulation and plasticity reserve exhaustion, which occur in, stress condition scheme index changing conditions Π [9-10]:

\[ \Pi = \frac{\sigma}{T} \]  \hspace{1cm} (1)

where \( \sigma \) - is the hydrostatic pressure (defined through the stress tensor first invariant)

\[ \sigma = \frac{1}{3} (T_\sigma) = \frac{(\sigma_{xx} + \sigma_{yy} + \sigma_{zz})}{3} ; \]  \hspace{1cm} (2)

\( T \) - the shear stresses intensity (defined through the stress deviator second invariant)

\[ T = \sqrt{I_2(D_\sigma)} = \frac{1}{\sqrt{6}} \sqrt{(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{zz} - \sigma_{xx})^2 + (\sigma_{yy} - \sigma_{zz})^2 + 6(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{zx}^2)} . \]  \hspace{1cm} (3)

The cumulative shear strain level Λ characterizes the strain condition and is defined as:

\[ \Lambda = \int_{0}^{t} H(\tau) d\tau \]  \hspace{1cm} (4)

where \( H \) - is the shear strains velocity intensity (defined through the strain velocity deviator second invariant)
\[ H = 2 \sqrt{I_2(D_{ij})} = \]
\[ = \sqrt{\left( (\xi_{xx} - \xi_{yy})^2 + (\xi_{yy} - \xi_{zz})^2 + (\xi_{zz} - \xi_{xx})^2 \right)^2 + \frac{4}{3} \left( \xi_{xy}^2 + \xi_{yz}^2 + \xi_{zx}^2 \right)^2}. \]  

Stress condition scheme index values defines each loading or unloading step maximum cumulative shear strain level \( \Lambda_p \) at which the metal fatigue crack nucleation will occur:

\[ \Lambda_p = f(\Pi) \]  

The plasticity reserve exhaustion level (PREL) \( \Psi \) is a complex parameter, that describes as stress and strain material condition. According to the Kolmogorov linear model the plasticity reserve exhaustion level is defined as [9]:

\[ \Psi = \int_a^t \frac{\Lambda}{\Lambda_p} d\tau. \]  

**Results and discussion**

As an example of obtained results the distributions of RS tensor components, cumulative shear strain level \( \Lambda \) and plasticity reserve exhaustion level \( \Psi \) at the SPD treated surface layer depth are shown (after 300 simulation step) (fig. 4).

![Fig. 4](image)

The residual stress tensor components, cumulative shear strain level \( \Lambda \) and plasticity reserve exhaustion level \( \Psi \) distribution in the surface layer depth after the 300-th simulation step (roller profile radius \( R_{pr} = 10 \) mm; preset roller tightness \( h_a = 0.05 \) mm; feed \( S = 0.1 \) mm/rot; workpiece rotation frequency \( n = 300 \) rpm)

The largest compressive stress values (up to \(-500 \) MPa) has an axial component \( \sigma_x \). These fact is favorable because of a significant influence of this component to the workpiece (machine part) cyclic durability during it operational (fatigue) loading at circuit bending with rotation. Also the axial component has the compressive stress extremum located at a depth of about 0.5 mm under the workpiece surface, the compressive stress distribution depth reaches 4 mm.

These values correspond to the experimental data, obtained in [7], where the axial RS value at SPD reaches \(-800 \) MPa, and the circumferential RS - up to \(-400 \) MPa.

RS formation picture is also correspond to the results obtained in [11] for the ball SPD treatment. The author marks the possibility of compressive RS extremum formation on the surface and at some depth.

The surface layer depth cumulative shear strain level (CSSL) distribution has a maximum value \( \Lambda = 0.267 \) at the surface and continuously decreases as the distance from the surface. The plasticity reserve exhaustion level has a similar distribution character, the maximum value for this treatment mode is \( \Psi = 0.047 \). The \( \Lambda \) and \( \Psi \) significant values depth distribution is 2-3 mm.
Conclusions
Overall, the picture is in agreement with the analytical and experimental results obtained by the earlier works authors.
As a modeling result the stress-strain distribution parameters and calculated surface layer mechanical condition and residual stresses, formed during SPD hardening treatment, parameters were obtained.
A proposed model feature is the TI phenomenon consideration not only at the the previous loading (treatment or operation) stages level, but at the current loading stage level, during metal particles displacement through the deformation zone space (the effect of the hardened body effect).
Accounting this, for hardened body effect percentage estimate (TI in current loading stage), using the proposed approach further the SPD treatment simulation without hardened body phenomenon consideration requires.

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