Theoretical bases of the surface layer formation in the finishing and hardening treatment of details by SPD in flexible granular environment

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Abstract. The article presents results of theoretical studies of the surface layer formation during finishing and hardening treatment of details by SPD in flexible granular environment. The dependencies are fixed for determining the surface roughness, processing time, the depth of the hardened layer and the degree of hardening for different methods of treatment by SPD in flexible granular environment. The process of residual stresses formation is researched.

1. Introduction
Methods of processing by the surface plastic deformation (SPD) in the flexible granular working environments are increasingly used in various industries at the finishing stages. They have fairly broad technological capabilities that allow processing the details of different shapes, ensuring high quality of the surface layer and achieving high processing performance.

It should be noted that the processing based on the plastic deformation of a thin surface layer (finishing and hardening treatment) using flexible environment has several advantages compared to other SPD finishing treatment methods: the metal fibers integrity is retained and a fine structure is formed in the surface layer; a treated surface charging with particles of abrasive is absent (if processing is performed in abrasive environment); no thermal defects; provides a stable surface quality; it is possible to achieve a minimum altitude of the surface roughness for crude steel, non-ferrous alloys and high-strength materials; it creates a favorable form of asperities with a high share of the supporting area at the level of roughness; favorable residual compressive stresses in the surface layer are created; surface microhardness increases; usually finishing and strengthening treatment with flexible granular medium (FST FGM) does not require the use of complex equipment and tooling; the FST FGM may use a variety of details of different shapes and sizes made of different materials [1-3].

On the basis of the studies, a generalized theory of FST FGM was created for finishing and hardening vibration treatment (FHVT), decorative and reinforcing centrifugal rotary processing (DRCRP), fraction processing (FP) and other similar methods.

2. Research results
In the study of the basic FST FGM methods of technological parameters (process performance and the quality of the treated surface) one of the most important issues is a question of theoretical modelling of the interaction process between the environment particles and the workpiece surface. The development of theoretical dependencies describing the shape and the size of the processing marks allows further movement to probability theory describing the distribution of the marks on the workpiece surface, which in turn makes it possible to develop a model of the roughness profile and physico-mechanical properties of the workpiece surface.

Deformation of irregularities in the FST FGM is as follows: a particle of environment interacts with protrusions of the workpiece surface microprofile resulting in plastic deformation causing the metal flow (in microvolumes), with plastic deformation occurring in the surface layer of the workpiece. This is due to a significant excess of working bodies hardness compared to the hardness of the processed material.

At the beginning of the interaction, the environment particle contacts the tops of the workpiece irregularities as an arc. The length of the contact segment increases with the introduction of the particle into the surface up to partial or total deformation of the asperities. Frictional force at the contact surface prevents asperities deformation in the circumferential direction. Shear stresses resulting from the interaction are maximal at the contact surface and decrease in the material with depth. The roughness increases at the contact of the surface with the environment particle and causes plastic flow of the metal towards the least resistance, i.e. in the direction of free surface - microroughness cavity. As a result of the efforts redistribution, the cavities ‘raise’ up to the contact with the processing body surface. This process is more intensive if the deformable protrusion is close to the zone of maximum pressures [1, 2].

The depth of the environment particle (mostly a metal ball) penetration can be determined by

$$h_{\text{max}} = 2 \cdot V_{ef} \cdot R \cdot \sin \alpha \cdot \sqrt{\frac{\rho_c}{3k_s \cdot c \cdot \sigma_s}}$$

where $V_{ef}$ is effective speed of the particle (determined by the characteristics of a particular treatment type), $R$ is the radius of the particle, $\alpha$ is the angle of particle falling to the workpiece surface, $\rho_c$ is the density of the particle material; $k_s$ is a coefficient taking into account the effect of the workpiece roughness; $c$ is a coefficient of the contact surface bearing capacity; $\sigma_s$ is the workpiece material flow ability limit.

For the fraction processing, this dependence is as follows:

$$h_{\text{max}} = 1.6 \cdot K_L \cdot R \cdot \sqrt{\frac{P_{\text{din}} \cdot \rho_c}{k_s \cdot c \cdot \sigma_s \cdot \rho_{cm}}}$$

where $P_{\text{din}}$ is dynamic pressure; $K_L$ is loss ratio, which takes into account the distance to the workpiece and the balls flux density (determined during experimental studies); $\rho_{cm}$ is the density of the mixture.

The volume of the surface layer deformation is largely determined by the physico-mechanical properties of the workpiece material and the number of interactions relating to each point of the treated surface. The contact stresses in the treatment zone under the influence of the environment particles depend not only on the force of impact, but also on the particle size and the height of the original protrusions.

Due to its dependence on the angle of impact and the shape of the initial roughness, the contact surface has a complex spatial form. In the case of processing with polished steel balls, ellipsoidal shape of the nominal contact surface seems to be possible. This greatly simplifies the further theoretical calculations.

The point of the particle contact with the surface is an ellipse, semiaxis sizes of which are
where \( f \) is a coefficient of the particle friction on the workpiece surface.

Plastic deformation of the workpiece surface occurs with repeated interaction of the environment particles with it. Individual wells with a transverse roughness are formed depending on the parameters of the original profile. The microrelief of the surface is formed by overlapping and crossing of individual tracks (holes).

If the process of treatment is stopped before the steady roughness formation, an increase of the profile bearing surface compared with the original one will be observed. Continuation of the process will lead to redeformation of the original roughness if the parts originally did not have very high hardness and significant initial roughness.

On the workpiece surface, a new specific micro-relief is formed, which is characterized by uniform properties in all directions. Under continued processing, it is permanently reproduced and its parameters will not change during a certain period of time (until the surface lapping). Parameters of the established roughness will be determined only by technological conditions and the size of environmental particles.

During the FST FGM the average arithmetic roughness deviation of the profile can be determined

\[
R_a_{yst} = k_R \cdot \sqrt{\frac{h_{max} \cdot a \cdot b \cdot l_{ed}}{R^2}},
\]

where \( l_{ed} \) is the length of the unit, \( k_R \) is an empirical coefficient.

For the fraction treatment, this dependence is as follows:

\[
R_a_{ust} = 0.009 \cdot \frac{b}{R} \sqrt{h_{max} \cdot l_{ed}}
\]

Reduction of the initial roughness height parameters during the FST FGM is complex. Therefore, obtaining a rigorous theoretical model to determine the processing time is not yet possible.

According to many researchers, the change in surface roughness is exponential. The speed of the new relief formation is reduced from its maximum in the initial period to values slightly different from zero at the time of the steady roughness formation, which indicates the formation of continuously replicating surface topography. Each combination of technological parameters corresponds to a specific density of interactions and the level of the environmental particles energy determining both the length of time and altitude parameters of the established relief, and the latter depend on the initial roughness.

The above conditions are met with

\[
R_a = \left( R_{a_v} - R_{a_{ust}} \right) e^{kt} + R_{a_{ust}},
\]

where \( R_{a_v} \) is arithmetic average deviation of the original surface roughness, \( k_i \) is coefficient of roughness intensity reduction, \( t \) is processing time, \( R_{a_{ust}} \) is set surface roughness.

Expressing the processing time from the resulting dependence we obtain the following formula:

\[
t_{zad} = \frac{1}{ki} \cdot \ln \frac{R_{a_{zad}} - R_{a_{as}}}{R_{a_{is}} - R_{a_{ust}}},
\]

where \( k_o \) is a coefficient of roughness intensity changes; \( R_{a_{ust}} \), \( R_{a_{is}} \), \( R_{a_{zad}} \) are original, set and specified surface roughness respectively.

For solving the FST FGM technological problems, analytical calculation of the expected value of the hardened layer depth and the degree of hardening is important. Many operational properties of the workpiece, such as fatigue strength, depend on the thickness of the hardened layer. Value \( h_s \) designates a zone of the surface layer, which has residual deformation and an increase of the crystal
lattice dislocation density formed by the application of external loads. Analytical determination of the hardened layer thickness and the degree of hardening depending on the physical and mechanical properties of the material and the process parameters is a very difficult task. Existing mathematical relationships were based on the theory of elasticity and plasticity after the adoption of numerous simplifications and assumptions. Significant researches in this area were conducted by I V Kudryavtsev, V P Pshibylski, E G Papshev and others. Using their dependencies, the FST FGM depth of the hardened layer and the degree of hardening can be determined by formulas:

$$h = 3k \sqrt{a \cdot b}, \quad \varepsilon = \frac{h_{\text{max}}}{R} \cdot \left(\frac{2 - h_{\text{max}}}{R}\right).$$

Formation of residual stresses in the FST FGM is of great research interest. In the works by R B Heywood [2] and V T Troshchenko, it is noted that the value of the endurance limit is affected by the average value of the cycle stress, the influence of which, in turn, can be compensated with the value of residual stresses.

Using the analysis of the cycle stress average value impact on the endurance limit for cyclically stable steels and aluminum alloys, the following equation is proposed for determining the limiting cycle stress:

$$\sigma_a (h) = \sigma_b \left(1 - \frac{\sigma_{cr} (h)}{\sigma_b}\right) \left[F + \gamma (1 - F)\right],$$

where $\sigma_b$ is the sample material strength limit; $\sigma_{cr}$ – residual stresses; $F$ and $\gamma$ are parameters depending on the sample material.

For the aluminum alloys samples

$$\gamma = \frac{\sigma_{cr}}{\sigma_b \left[1 + \left(\frac{\lg N_p}{225}\right)^4\right]}; \quad F = \left[1 + \frac{0.0031 \left(\lg N_p\right)^4}{1 + 0.0031 \left(\lg N_p\right)^4}\right]\left(1 + 0.0031 \left(\lg N_p\right)^4\right)$$

For steel samples

$$\gamma = \frac{\sigma_{cr} (2 + \sigma_{cr}/\sigma_b)}{3\sigma_b}; \quad F = \frac{1 + 0.0038 \left(\lg N_p\right)^4}{1 + 0.008 \left(\lg N_p\right)^4},$$

where $N_p$ is the number of cycles before destruction.

3. Conclusions

The results of studying surface residual stresses formed after various kinds of FST FGM allows making a conclusion that compressive residual stresses are formed in the workpiece surface layer at a depth of 0.2...0.8 mm of 200...300 MPa that allows one to predict the improvement of the workpieces operational properties.

The generalized theory has passed a comprehensive experimental verification, and can be used to design the FST FGM processes that enhance the quality of the workpieces surface layer. On its basis, a method of the FST FGM technological processes optimization is created.

References

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