Energy-efficient OMD processes with complex local loading for the production of machine parts with a given level of properties

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Abstract: The article discusses some new energy-efficient metal forming processes (PMD) with complex local loading of the deformation zone for the production of machine parts with a given level of properties. The place of such processes in the aggregate of all OMD technologies is shown, and their classification is given. The initial data of numerical mathematical modeling of the specified class of processes for a particular case are given, the features of the stress-strain state of the metal in the deformation zone are revealed. In the study, from a theoretical point of view, one of the important practical aspects of these technologies is considered: the effect of the value of axial compression on the shape and size of the deformation zone arising from the action of local loading of the workpiece.

1. Introduction
Advancements in mechanical engineering are raising the bar ever higher. Today, any new casting, cutting, or forming technology is expected to surpass its predecessor as well as to compete against additive technologies. The authors hereof develop and implement technologies based on complex local loading of the deformation zone (CLL deformation) as part of the broader metal forming research. CLL deformation represents a set of metal forming processes, which create a plastic deformation zone by applying multiple loads, one of which affects the bulk of the workpiece and is referred to as global loading; the rest is local and is intended to generate a non-stationary deformation zone characterized by a complex stress state. [1-10]

2. Statement of Problem
Before delving deeper into the problem, let us define the complex and local loads. Complex loading (CL) is the process of applying two or more independent forces and/or moments to a workpiece. Torsional tensile tests are a classic example. Apparently, CLL deformation imposes a complex load upon the workpiece material [4-8]. This infers the following definition: CL is a process that subjects a workpiece to two or more independent loads, which entails a complex non-homogeneous stress state in the deformation zone.

If this or that metal forming technology implies deliberately localizing the deformed material in a non-stationary plastic flow zone that is far smaller than the bulk of material deformed by a single operation, this is a local loading (LL) process. Spacing operations that deform a sheet, e.g. bending or flanging, are non-LL, as they cause plastic deformation limited to a particular location, i.e. unlike in drawing, the instant deformation zone does not move along the workpiece. Pressing and rotational forging processes are not local either; although the instant deformation zone is limited in scale, the process deforms the bulk of the workpiece to transfer pressure. Thus, local deformation only comprises the processes that limit active deformation to a specific spot that moves along and/or within the workpiece. Hence the definition: local loading is a process that is intended to create a local active non-stationary deformation zone.

Let us present the general CLL deformation diagram to better describe the concept. The workpiece is globally loaded by a system of forces and moments shown in Figure 1 as a distribution of stresses f. The workpiece is also locally deformed by the tools 1, 2, … n that follow the trajectories Ω₁, Ω₂, etc. The tools localize the deformation zone to intensify the plastic flow in a small part of the workpiece.
As the tools and the workpiece are displaced with respect to each other, the deformation zone moves. As a result, one part of the workpiece is subjected to single or multiple loading for more efficient reshaping and/or hardening [1-10].

From the standpoint of machining goals, CLL deformation processes can be systematized as follows [1-5].

1. Reshaping CLL deformation that seeks to alter the shape; hardening may occur as a not necessarily desirable side effect. Reshaping can be mainly attained by:
   - global loading, in which case local loading is auxiliary;
   - local loading, in which case global loading is auxiliary and serves to improve the stress state diagram. As such, it can be imposed indirectly by form locking;
   - a combination of global and local loading.

2. Hardening CLL deformation, in which case global loading is auxiliary and serves to improve the stress state diagram. As such, it can be imposed by:
   - applying a static load that does not cause any stress equal to, or exceeding the yield point;
   - indirectly by form locking.

3. Combined CLL deformation, which seeks to reshape the material while also improving its structure and the product strength. As such, it combines active global and local loading.

Diagrams 1.2 and 2.1 are preferable from the standpoint of energy conservation and ease of use. These are processes where the global loading component serves to adjust the stress state diagram and does not cause any stress that would equal or exceed the yield point of the workpiece material. To analyze these CLL deformation processes, dissect the general CLL deformation diagram with a plane that passes through the forming tool and the smoothing tool, see Figure 2.

Distributed load can be applied in various ways, see Figure 3. When implemented, Option a implies that the workpiece move along the supporting surface; at \( p_1 = p_2 \), the workpiece travel speed is constant, no stress emerges in the deformation zone, which means this option is useless. At \( p_1 < p_2 \) or \( p_1 > p_2 \), the workpiece movement is associated with additional forces emerging in the deformation zone under the tools 1 and 2; however, the magnitude of such forces is the difference of \( p_1 \) and \( p_2 \), making machining less efficient. Thus, Option a is hardly usable.

With Option c as shown in Figure 3, the distributed loads \( p_1 \) and \( p_2 \) cause tensile stresses in the workpiece body; with Option b, the stresses are compressive. Thus, there are four practically applicable global loading options for CLL deformation in processes where global loading is intended to alter the stress-state diagram, see Table 1.
Figure 2. CLL deformation: general diagram section.

Figure 3. Applications of distributed load: 1 and 2 are local deformation tools (shown as one for simplicity); 3 is the workpiece.

Apparently, the values $p_1$ and $p_2$ can significantly affect the plastic flow of metal when machining. It is therefore important to analyze how compressive and tensile forces affect the stress-strain state in such CLL deformation processes where such forces do not cause any stress that would exceed the yield point.

Table 1. Practical CLL deformation technologies where the global load does not cause any stress in excess of the yield point.

| Global load application options | $p_1 = p_2$ | $p_1 < p_2$ |
|-------------------------------|-------------|-------------|
| $b$                           | hardening CLL deformation | -           |
| $c$                           | Pull-backpull rolling: particular case | Pull-backpull rolling: general case |
Let us assess the effects of axial compression in case of hardening CLL deformation, i.e. Option \( b \) at \( p_1 = p_2 \). Tests are based on mathematical modeling in Stamp package [2].

The problem-solving algorithm is based on a mathematical model that uses a well-known variation principle:

\[
\int \int \int_{V(t)} \delta \nabla \cdot \left( \tau \sigma - d \sigma - \sigma \cdot \omega + w \cdot \sigma - \sigma \cdot w + (\nabla \cdot v) \sigma \right) dv = \\
= \hat{Q} \cdot \delta \hat{q} + \int \int_{S(t)} \delta v_t \cdot (\hat{p} + p(\nabla \cdot \nu - n \cdot d \cdot n)) dS, \\
\]

(1)

where \( \sigma, d, \omega \) are the Cauchy stress tensor, the strain-rate tensor, and the rotation-rate tensor, respectively.

\( p, n \) are the pressure and the external normal relating to the actual contact surface \( S(t) \),

\( \hat{p} \) is the pressure rate,

\( r \) is the co-rotational derivative in the constitutive equation for the material of the deformed solid,

\( \nabla \cdot v \) is the velocity field gradient,

\( \hat{Q} \) are generalized-force velocities,

\( \delta \nu_t \) are variations of the velocities of sliding along the surface of an absolutely rigid solid,

\( \delta \dot{q} \) are variations of generalized velocities.

Integration (1) by the volume \( V(t) \) and the contact surface \( S(t) \) at time \( t \).

The equation (1) is a modified velocity variation principle proposed in 1983 by L.A. Tolokonnikov, O.L. Tolokonnikov, A.A. Markin and V.F. Astapov, later advanced by P.G. Morev [2-5].

The velocity field gradient \( \nabla v(y) \) is defined as:

\[
\nabla v = \gamma^i \frac{\partial v}{\partial y^j} = \nabla_i \dot{y}^j \gamma^i \otimes \gamma_j = \nabla_i \dot{y}^j \gamma^i \otimes \gamma_j ; \\
\]

(2)

The gradient of the velocity field \( \nabla v^T \) is defined as:

\[
\nabla v^T = \frac{\partial v}{\partial y^j} \gamma^i = \nabla_i \dot{y}^j \gamma^i \otimes \gamma_j = \nabla_i \dot{y}^j \gamma^i \otimes \gamma_j ; \\
\]

(3)

the strain-rate tensor is defined as:

\[
d = \frac{1}{2} (\nabla v + \nabla v^T) , \\
\]

(4)

the rotation-rate tensor is defined as:

\[
\omega = \frac{1}{2} (\nabla v^T - \nabla v) , \\
\]

(5)

the velocity field of the material points of the solid determines their law of motion

\( \dot{y}(y, t) = \nu(y, t) \).

The following ratio is used as the constitutive equation for the strain-rate tensor \( d \) and the stress tensor \( \sigma \)

\[
\dot{\gamma} \sigma = D \cdot d , \\
\]

(6)

where \( j \) is Yauman’s derivative,

whereas tensor \( D \) is written as follows in global Cartesian coordinates:
\[ D_{ijkl} = \begin{cases} \frac{E_{ijkl} - \frac{3G S_{ij} S_{kl}}{\sigma^2 (1 + H'/(3G))}}{E_{ijkl}} & \text{under active loading} \\ \frac{E_{ijkl}}{E_{ijkl}} & \text{under reversible loading} \end{cases} \] (7)

where \( E_{ijkl} \) is the isotropic tensor of elasticity,
\( S_{ij} \) is the stress-tensor deviator,
\( \sigma \) is the stress intensity,
\( H' \) is the hardening modulus,
\( G \) is the shear modulus.

Here is the condition of elastic-to-plastic state transition:
\[ \sigma = H(q), \] (8)

where \( H(q) \) is the hardening curve.

Mathematical modeling relies on the isotropic theory of plasticity with low elastic deformation, as hardening uses cyclical or nearly cyclical workpiece deformation. Odqvist parameter increments are rather small for each cycle. Therefore, the reversibility surface will not differ much from a circumference, hence no contradiction to the actual deformation. The evolutionary equation of stress state is then written as follows:
\[ \dot{\sigma} = \dot{\sigma} - \sigma \Omega + \Omega \sigma, \] (9)

where \( \Omega \) is the rotation speed of the material point neighborhood.

To solve the equation (2) numerically, discretize its left side and use the constitutive equation written as:
\[ r^\sigma = D \cdot \nabla v. \] (10)

The mathematical model uses Coulomb’s isotropic law with a constant coefficient of friction \( \mu \) that links the tangent pressure component \( p_t \) and the normal pressure component \( p_n \):
\[ |p_t| \leq \mu |p_n|. \] (11)

The mathematical model describes the quasi-static interaction of rigid solids with a finite elastoplastic solid. Finite-element analysis is used to solve the system of reduced equations (1), (6)-(11).

Figure 4 presents the calculation diagram for mathematical modeling. Calculation uses the following boundary conditions:
- nodes in contact with the indenter may not move inside the tool;
- nodes in contact with the hatching may not move at all.
The injectable body is a toroidal roller, 0.5 mm in radius. To simulate the power action of the roller, use relative injection depth defined against the workpiece thickness. Find the axial compression as a fraction of the yield point for the material under consideration $\sigma_T = \sigma_0$.

3. Results

Figure 5 shows the results of modeling the injection of a toroidal tool into the workpiece body to a relative depth of 0.02 at different axial compression magnitudes. These are Odqvist parameter isolines at zero. Thus, what is shown in Figure 5 effectively defines the hardened zone of the workpiece. Figure 5 clearly shows that in case of axial compression, the hardened zone for a toroidal roller splits into two petal-shaped zones. Note that similar phenomena occur with other tools, too, see Figure 6. As shown in Figure 6, the applied axial force must exceed $0.9\sigma_0$ for the hardened zone to grow.
Table 2 presents data on increasing the relative hardening depth and peak Odqvist parameter value at maximum vs zero axial compression. Apparently, the hardening depth and magnitude peak when applying extra axial compression at low injection depth. It should be noted that maximizing the Odqvist parameter is not necessarily desirable, as it can destroy the product [1, 6-10].

Table 2. Relative growth of Odqvist maximum value and relative depth of hardening at different depth of implementation and geometry of indentors for $p_{wasp}$ values compared to $p_{wasp} = 0$.

| relative injection depth | 0.002 | 0.004 | 0.008 | 0.012 | 0.016 | 0.020 |
|--------------------------|-------|-------|-------|-------|-------|-------|
| increase in the peak Odqvist parameter value, % | 22.02 | 20.24 | 19.12 | 16.44 | 16.09 | 15.44 |
| increase in the relative hardening depth, % | 144.09 | 72.71 | 41.16 | 17.59 | 6.50 | 1.93 |

4. Experimentation

Based on the diagram shown in Figure 1, the research team developed a process, see Figure 2, that effectively performs complex local loading of the deformation zone for the purpose of hardening. The global load application option for this method is $b$ at $p_1 = p_2$. The workpiece in use was the bush 1, see Figure 2. The local deformation tool was the special lugged roller 5. Like the roller, the roller matrix 4 was used for local deformation. The workpiece was driven by stops through a rigid geometric connection. Machining was performed in the three-roller matrix 4. Hardening started at the outer surface; the inner surface rested on the frame 3, which controlled and constrained the plastic flow of metal.

It’s no coincidence we selected a bush for experimental CLL deformation, as most parts that require improved mechanical properties are axisymmetric (shafts, axles, sleeve bearings, piping products). Should be noted that there’s no fundamental difference between machining bushes as shown in Figure 7, pipes, axes, and shafts. Using rollers for local loading was also an obvious solution that reduced friction losses. The lug had to geometrically match the process diagram and feature a symmetry axis, as the tool moved reciprocally.

The significant process parameters were determined following the method description (Figure 7) and the general diagram (Figure 1).

1. Geometry and shape of the forming tool for the roller 5.
2. Number of passes, i.e. the number of closed trajectories $\Omega_1$ the forming tool 1 follows when traversing the workpiece surface. For the technology shown in Figure 2, it corresponds to the number of roller passes along the workpiece.
3. Loading force (the tool injection depth $\Delta$) is the force $P$ applied to the roller.
4. Forming tool feed pitch ($s$ in Figure 7) is a parameter of the trajectory $\Omega_1$. When machining an axisymmetric product, the trajectory $\Omega_1$ is a helix. The workpiece 1 in Figure 2 rotated around its axis while the roller 5 moves in parallel to this axis at the speed $\nu$, which meant the feed pitch was the helix pitch.
The smoothing tool (Figure 7) restores the surface to its original geometry after the forming tool had passed. Global loading had the force $P$, which for these experiments was form-locking, i.e. $p_1 = p_2 = 0$. Experiments for cases when $p_1 = p_2 > 0$ are work in progress. In case of force closure, the force $P_{oc}$ should not cause any stress in the workpiece body equal to, or exceeding the yield point provided zero sundry load, i.e.

$$P_{oc} < \sigma_y \cdot \frac{\pi \cdot (D^2 - d^2)}{4},$$  (12)

where $D$ is $d$ the workpiece inner/outer diameter.

Experiments used specially designed tooling that could vary the force (the roller injection depth), the tool geometry, the number of passes, and the feed pitch. Processing the experimental data produced the distribution curves of microhardness ($H_{\mu}$) as a function of distance to the surface ($h_{\mu}, \mu$m) and number of passes ($n$) at a certain tool force ($P$, $H$), see Figure 8 as an example [8-10].

**Figure 7.** Hardening CLL deformation diagram:  
1 is the workpiece; 2 are stops; 3 is the frame; 4 is the roller matrix (a smoothing tool); 5 is the lugged roller (a forming tool); $M_g$ is the moment applied to the workpiece; $\nu$ is the roller travel speed; $P$ is the force applied to the roller to control the injection depth; $P_{oc}$ is the force applied to the stops, $s$ is the feed pitch.
Figure 8. Distribution of microhardness values in the coordinates $H_\mu - h_\mu$ for the hardening CLL deformation at different pass numbers and $P = 310$N; points A are surficial, points B are located at the interface of hardened/non-hardened areas (experimental data approximated by the least squares). Squared dots show the experimental distribution of microhardness parameters for $n = 38$ and $P = 310$N.

5. Discussion
The hardened zone features pronounced “petals” when exposed to axial compression at $p_{oc} > 0.9$. A closer look at the stress distribution in the deformation zone (Figure 9) sheds some light. As shown in the figure, zones featuring $\sigma_{xr}$ and $\sigma_{zr}$ (values of stresses $\sigma_x$ and $\sigma_z$ normalized to $\sigma_0$) are similar in size and geometry. However, the entire workpiece is stressed in the longitudinal section for $p_{oc} = 0.99\sigma_0$, see Figure 9. This is due to the fact that in this plane, workpiece parts are closer to a transition to plastic state prior to tool injection than in any other plane as they are exposed to axial compression. Thanks to these “petals”, the hardened zone actually splits into two components.
This is a significant advantage of the methods that apply extra load. Given that hardening CLL deformation is associated with longitudinal feed at a certain pitch, the petals to the left and to the right of the roller path will inevitably intersect. Apparently, each individual petal will, all other things being equal, pass the same portion of the workpiece twice, which means applying an axial load $p_{oc} > 0.99\sigma_0$ makes machining twice as efficient as applying zero axial compression.

6. Conclusions
The paper considers metal forming by local loading of the deformation zone. The method is described and classified as a part of the metal forming technology. Theoretical analysis covers one of the most important aspects of this technology, i.e. how axial compression affects the geometry of the deformation zone created by locally loading the workpiece. The paper shows that applying axial load in machining is appropriate as long as the load is 90% to 99% of the yield point when CLL deformation is used for hardening. It is also shown that all other things being equal, axial compression can double the efficiency of machining.

REFERENCES

[1] V.A. Golenkov, S.Yu. Radchenko, D.O. Dorokhov, and G.P. Korotkii, “Scientific Foundations of Strengthening via the Combined Local Deformation”, Moscow: Mashinostroenie; Oryol: State University, UNPK, 2013

[2] Yakovlev, S.S., Tregubov, V.I., Osipova, E.V. Limiting deformation in rotary drawing of anisotropic pipe blanks with wall thinning Russian Engineering Research 36(6), 2016, 472-475
[3] Yakovlev, S.S., Polikarpov, E.Yu. Extension of thick-walled cylindrical anisotropic blanks, with thinning of the wall. Russian Engineering Research 29(7), 2009, 698-704

[4] Morrev, P. G. (2011). A Variational Statement of Quasistatic “Rigid-Deformable” Contact Problems at Large Strain Involving Generalized Forces and Friction. Acta Mech, 222, 115-130. http://dx.doi.org/10.1007/s00707-011-0516-9

[5] Morrev, P. G., Fedorov, T.V. A nurbfs approximation of experimental stress-strain curves. Journal of Chemical Technology and Metallurgy. 2016, 51(3). 341-349.

[6] Fedorov, T.V. Approximation of experimental hardening curves by inhomogeneous fractional rational B-splines [Text] / T.V. Fedorov // Fundamental and applied problems of engineering and technology. 2014. № 1 (303). 64-68.

[7] Morrev, P.G., Gordon, V.A. Simulation of surface hardening in the deep rolling process by means of an axial symmetric nodal averaged finite element. Journal of Physics: Conference Series. 2018, 973(1),012013.

[8] Morrev, P.G., Gordon, V.A. An axisymmetric nodal averaged finite element. Latin American Journal of Solids and Structures. 2018. 15(2),e14

[9] Pilipenko, O.V., Radchenko, S.J., Golenkov, V.A., Dorohov, D.O. Numerical Mathematical Simulation of Penetration of Indenters of Different Shapes During Strengthening Machine Parts via Local Loading of Deformation Zone // International Symposium on Engineering and Earth Sciences (ISEES 2018). Advances in Engineering Research, volume 177, 568-573.

[10] Pilipenko, O.V., Radchenko, S.J., Golenkov, V.A., Dorohov, D.O. Gradient Strengthening Control Procedure Based on Numerical Simulation of Combined Local Loading Of Deformation Zone // International Symposium on Engineering and Earth Sciences (ISEES 2018). Advances in Engineering Research, vol. 177, 574-577.