Development of mathematical models for automation of strength calculation during plastic deformation processing

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Abstract. Dependencies that make it possible to automate the force calculation during surface plastic deformation (SPD) processing and, thus, to shorten the time for technological preparation of production have been developed.

1. Introduction
To automate the selection of the finishing-hardening treatment by surface plastic deformation (SPD FHS), it is necessary to calculate the dependencies of the achieved quality parameters of the part on the processing mode.

The main parameters of the SPD mode are force (F), feed (S_o) and processing speed (V). Strength affects both physical and mechanical, as well as the geometric characteristics of the quality of the surface layer of machine parts. Varying the force, it is possible to form the required type of SPD FHT (finishing, finishing-hardening or strengthening) [4-6, 9, 10].

2. The study of the theoretical bases of the SPD FHT
SPD FHT can be carried out in finishing, finishing-strengthening and strengthening regimes.

Finishing treatment of SPD (Figure 1) is performed to reduce the initial roughness of the surface, increase its bearing capacity. The surface hardening coefficient is in the range of 1 < k < 1.05 [3].

![Figure 1. Surface profile of the workpiece after finishing processing (rolling of steel samples of 40X (25HRC) with a ball-point runner, D_{ball} = 10mm, F = 30N).](image)

Finishing-hardening treatment of SPD (Figure 2) is carried out to reduce the initial surface roughness, increase its bearing capacity and partial surface hardening of the workpiece. The hardening coefficient is in the range of 1.05 < k < 1.3 [3].
The reinforcing treatment of SPD (Figure 3) is performed with the aim of restoring the initial roughness and hardening of the surface layer of the workpiece. The coefficient of hardening is $1.3 < k < 2$ [3].

In determining the force during the SPD processing, it is assumed that for small feeds, the actual contact area of the working tool with a rough surface is equal to the formed area at the level of $p_{\text{cont}} = 5\%$, and hence:

$$ t_{p_{\text{cont}}} = t_{5\%} . $$

For finishing processing $t_{p_{\text{cont}}} = t_{5\%} = (10...30)\%$, for finishing-hardening processing $t_{p_{\text{cont}}} = t_{5\%} = (30...80)\%$, for strengthening processing $t_{p_{\text{cont}}} = t_{5\%} = (80...100)\%$.

According to the theory of contacting solids, the actual contact area during plastic deformation is determined by the equation [3, 8]:

$$ A_{\text{act}} = \frac{F}{Ck\sigma_T}, \quad (1) $$

where $F$ – force;
$C$ – restraint coefficient ($R = 2.87$);
$k$ – hardening coefficient;
$\sigma_T$ – workpiece material yield strength;

Wherein:

$$ A_{\text{act}} = A_n \cdot \frac{t_{p_{\text{cont}}}}{100}, \quad (2) $$

where $t_{p_{\text{cont}}}$ – the relative length of the initial roughness profile, in contact with the working tool, in $\%$;
$A_n$ – the nominal contact area of the working tool with the workpiece surface to be machined (geometric).
\[ A_n = \frac{F}{p_n}, \quad (3) \]

where \( p_n \) – the nominal pressure in the contact of the working tool and the workpiece surface of the workpiece.

Substituting (3) into (2), then equating the right-hand sides of the resulting equation and (1), one obtains:

\[ \frac{F \cdot t_{p_{cont}}}{p_n \cdot 100} = \frac{F}{Ck\sigma_t}, \]

whence:

\[ k = \frac{100 \cdot p_n}{C\sigma_t \cdot t_{p_{cont}}}. \]

硬固化的系数对于不同的 SPD FHT是:

1) 精加工处理:
\[ 1 < k < 1.05; \quad (5) \]

2) 精加工-硬固处理:
\[ 1.05 < k < 1.3; \]

3) 硬化处理:
\[ 1.3 < k < 2. \]

After substituting expression (4) into system (5), one obtains for:

1) 精加工处理:
\[ 0.3\sigma_t < p_n < \sigma_t; \]

2) 精加工-硬固处理:
\[ \sigma_t < p_n < 3\sigma_t; \]

3) 硬化处理:
\[ 3\sigma_t < p_n < 5.74\sigma_t. \]

In the case of SPD FHT, the force is determined by the expression:

\[ F = A_n \cdot p_n, \quad (6) \]

The nominal contact area of the tool with the surface to be treated is determined from the equation:

\[ A_n = 2\pi Y_{cont} \cdot r, \]

where \( Y_{cont} \) – contact deformations in the contact area of the tool and workpiece when sliding or rolling;

\( r \) – reduced radius in contact of tool and workpiece.

At pressures above the critical ones, under condition 3, the appearance of the effect of embrittlement and, consequently, softening of the workpiece surface layer can occur.

Solving these inequalities for force \( F \), one obtains:

1) for finishing treatment:
\[ 0.6\pi \cdot Y_{cont} \cdot r \cdot \sigma_t < F < 2\pi \cdot Y_{cont} \cdot r \cdot \sigma_t, \]

2) for finishing-hardening treatment:
\[ 2\pi \cdot Y_{cont} \cdot r \cdot \sigma_t < F < 6\pi \cdot Y_{cont} \cdot r \cdot \sigma_t, \]

3) for hardening treatment:
\[ 6\pi \cdot Y_{cont} \cdot r \cdot \sigma_t < F < 11.5\pi \cdot Y_{cont} \cdot r \cdot \sigma_t, \]

4) for softening treatment:
\[ F > 11.5\pi \cdot Y_{cont} \cdot r \cdot \sigma_t. \]
The contact approach for sliding or rolling is determined from the equation:

\[ Y_{c_{\text{cont}}} = Y_c \cdot \left( 2 \sqrt{1 + f^2} - 1 \right), \]

where \( f \) – coefficient of friction, sliding or rolling; \( Y_c \) – contact deformation in statics.

\[ Y_c = Y_{c_{\text{el}}} + Y_{p_{\text{pl}}} , \]

where \( Y_{p_{\text{pl}}} \) – plastic deformations in static (when the tool contacts a rough surface).

\[ Y_{p_{\text{pl}}} = Rz \left( \frac{2F}{A_n Ck \sigma_T} \right)^{0.5} , \]

\( Y_{c_{\text{el}}} \) – elastic contact deformations in static (when the tool contacts a rough surface).

\[ Y_{c_{\text{el}}} = 20 \left( 1 - \frac{\mu^2}{E} \right) Ck \sigma_T \cdot Y_{p_{\text{pl}}}^{0.5} , \]

where \( \mu \) - Poisson's ratio (for 0.3 steel),

\( E \) - material elasticity modulus (2 \( \times 10^5 \) MPa).

3. Materials and methods

Studies on the processing of external surfaces were carried out on samples of 40X steel of different hardness. The sample is a cylinder with a diameter of Ø37 mm and a length of 100 mm (Figure 4).

For rolling with a one-ball point runner, the authors used improved 40X steel, hardness 25HRC (heat treatment: quenching in oil with the temperature of 840 °C, tempering of 650 (20 min), followed by air cooling).

For diamond smoothing and rolling of hardened steel, tempered 40X (840 °C) steel was used, followed by tempering (450 °C), with the hardness of 34HRC.

![Figure 4](image)

**Figure 4.** An example of the sample: a - sample before treatment; b - sample after treatment and polishing.

With the help of theoretical dependencies, the ranges of forces providing for finishing, finishing-hardening and hardening SPD treatment were calculated (Table 1).
Table 1. Calculation of ranges of forces on theoretical dependences

| Treatment method          | Hardness, HRC | Yield strength, MPa | SPD FHT type                  | Range of rolling forces, F, N |
|---------------------------|---------------|---------------------|------------------------------|-------------------------------|
| One-ball rolling (D=10mm) | 25            | 500                 | finishing, finishing-hardening | 7…41.3 41.3…192.8 192.8…425.6 |
| One-ball rolling (D=10mm) | 34            | 785                 | finishing, finishing-hardening | 28.8…169.7 169.7…792.2 792.2…1747 |
| Diamond smoothing (r=1.5mm) | 34           | 785                 | finishing, finishing-hardening | 6.7…39.4 39.4…184.1 184.1…408.8 |

After processing the samples on a 16K20 screw-cutting lathe, the parameters of the surface layer quality (surface roughness and depth of the hardened layer) were measured. The roughness of the samples was measured on the ASNI on the basis of the profilometer-profilograph of 170311 model and the Mahr MarSurf PS1 profilometer. To determine the microhardness and the hardening degree, a PMT-3M microhardness meter was used.

4. Conclusion
Table 2 presents the experimental and theoretical values of the coefficient of surface hardening and depth of hardening the samples ($k_{\text{experim}}$, $k_{\text{theor}}$, $h_{\text{experim}}$, $h_{\text{theor}}$) when rolling by a one-ball point runner hardened steel 40X (hardness 34HRC).

Table 2. Experimental and theoretical data on 40X (34HRC) steel rolling

| Force, F, N | Treatment type | $k_{\text{theor}}$ | $k_{\text{experim}}$ | Ra, µm | Rz, µm | Rp, µm | $h_{\text{theor}},$mm | $h_{\text{experim}},$mm |
|-------------|----------------|-------------------|----------------------|--------|--------|--------|---------------------|------------------------|
| 125         | turning        | -                 | -                    | -      | -      | -      | -                   | -                      |
| 250         | finishing      | 1.08              | 1.03                 | 0.716  | 3.21   | 1.28   | 0.282              | 0.25                   |
| 500         | finishing-hardening | 1.01          | 1.08                 | 0.461  | 2.26   | 0.74   | 0.399              | 0.32                   |
| 1000        | finishing-hardening | 1.18          | 1.18                 | 0.213  | 1.36   | 0.42   | 0.564              | 0.45                   |
| 1750        | hardening      | 1.22              | 1.52                 | 0.144  | 0.56   | 0.25   | 0.798              | 0.6                    |

As a result of the experiment, it was found that in the case of hardening, it is recommended not to exceed the calculated value of the force; it has been experimentally confirmed that this leads to a deterioration in quality (an increase in the roughness and softening of the surface layer).

With an increase in the value of $k$ (finishing-hardening and strengthening regimes), the experimental data differ significantly from the theoretical ones (up to 40%). Therefore, it is necessary to introduce a correction factor in the dependence for the calculation of forces for finishing-hardening and hardening processing. In the source [7], the author notes that it is necessary to take into account
the dynamics of the SPD process and in the calculated dependences it is necessary to substitute \( \sigma_t \), 2... 2.5 times exceeding the tabulated values. If one assumes that the yield strength of the strengthened material increases in direct proportion to the hardening coefficient, then \( \sigma_t^c = k \sigma_t \). Then the dependencies for calculating the ranges of forces will take the form:

1) For finishing treatment:
\[
0.6 \pi \cdot Y_{\text{cont}} \cdot r \cdot \sigma_t < F < 2.1 \pi \cdot Y_{\text{cont}} \cdot r \cdot \sigma_t.
\]

2) For finishing-hardening treatment:
\[
2.1 \pi \cdot Y_{\text{cont}} \cdot r \cdot \sigma_t < F < 7.8 \pi \cdot Y_{\text{cont}} \cdot r \cdot \sigma_t.
\]

3) For hardening treatment:
\[
7.8 \pi \cdot Y_{\text{cont}} \cdot r \cdot \sigma_t < F < 23 \pi \cdot Y_{\text{cont}} \cdot r \cdot \sigma_t.
\]

4) For softening treatment:
\[
F > 23 \pi \cdot Y_{\text{cont}} \cdot r \cdot \sigma_t.
\]

Thus, theoretical dependencies, confirmed experimentally and allowing automation of the calculation of the force during the SPD processing, are obtained, providing the required type of SPD (finishing, finishing-hardening or reinforcing).

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