Connection between machines durability during operation and the complex of physic-mechanical properties, formed during the production of critical parts

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Abstract. The paper presents the effect of the processing technological structure on the hardening of metals and alloys by choosing the rational parameters of thermomechanical forming components at various stages of processing. The dependencies that can predict the destruction of the product during operation, depending on the structure of the resulting metal fabrication are shown.

1. Introduction
Among mechanical engineering resources consumed metals and alloys play a special role by virtue of the inherent complex of unique physic-chemical and technological properties that constitute a constructive foundation of modern machines and are the subject of processing at the main stages of their production. Metals constitute 96% of a total aggregate of structural materials used (including plastics, composites, etc.). Improving the metal quality leads to economic effects in different sectors, where the metal is transformed into structures and in their operation, due to the increased performance and technical features of a machine made of it.

2. Basic part
By virtue of the relationship and interdependence of different stages of the life cycle (see Fig. 1), increased efficiency - reducing costs while operating the machine, due to the improvement of its technical parameters (power, durability, reliability, etc.) often results in costs increase in production, as the improvement of these parameters is often associated with the introduction of additional strengthening heat treatment operations or application of high expensive construction materials.
Fig. 1 Connection (relationship) of structural materials service and technological properties with parameters of durability and efficiency of transport vehicles
Nevertheless, the increase in costs in the production system, aimed at improving the service properties of structural materials, and consequently, an increase in durability, even leading to an increase in prices, it is advisable, since gains from increased durability far exceeds the reduction in economic
effect due to increased cost of an automobile. Thus, an increase in durability relative to the average value of 3 times, followed by twice the automobile costs rise also 3 times increases the production economic effect [1].

Moreover the use of all technological possibilities for metals and alloys hardening by means of the rational choice of parts forming thermomechanical parameters at different stages of processing operation allows improving durability without introducing additional heat treatment that further enhances the economic efficiency associated with machines operation and connected with service properties of constructional materials used.

The connection of structural materials service and technological properties with the durability and efficiency of transport vehicles is displayed in Figure 1.

Durability of machine parts during operation depends on the processes occurring in the metal in operation and leading ultimately to the sudden or gradual failures. The greatest danger is sudden failures of parts, which can lead to a crash and serious damage to the whole machine. The destruction of deformation (ductile fracture), brittle and fatigue damage leads to the sudden failure. Each type of failure other than structural and operational factors, depends on the parameters of the structure and mechanical properties of the metal parts.

One of the reasons causing the destruction of parts during operation, is the aging of the metal [2; 3; 4, 5, 6].

In the first stages of aging (the appearance of submicroscopic inhomogeneities in the distribution of solute atoms in a supersaturated solid solution, the formation of dispersed particles and the establishment of a coherent communication grids) occurs strengthening of the alloy. The final aging step leads to coagulation of precipitated dispersed particles, the loss of new phase gratings and solid solution coherence, the solid solution depletion during the extraction process and results in the alloy destruction. The alloy strength changing at this step is described by the equation [4]:

$$\ln \sigma = \ln \sigma_k - k''t e^{-Q/R},$$

where $\sigma_k$-the strength of alloy after hardening treatment and artificial aging (initial strength); $\sigma$ - the current value of strength, $k''$- integral factor comprising constants $k$ and $k'$, depending on the nature of the material and component concentration; $t$ - aging time; $Q$ - activation energy, $R$ - energy of the reaction. On the assumption of the equation the strength decreases with time exponentially with the external environment characteristics constancy. Until a certain moment the $\sigma$ part strength will be sufficient to withstand the attached load $L$. It will be a period of no-failure operation. However, due to the aging of the material, after some period $t$, the strength is reduced to the level that does not conform to the load $L$, leading to the destruction (failure).

Knowing the initial strength and the load the material durability, and therefore part durability, taking into account aging equation can be calculated from the following relationship:

$$t = \frac{1}{k''(\ln \sigma - \ln L)} e^{-Q/R}$$

Product life improvement due to the material can be achieved by its initial strength increase and the softening aging rate reduction, as well as removing in it the macrodefects of critical dimension. The latter can cause brittle fracture already at relatively low operating stresses. The adverse tensile technological residual stresses as a rule have a significant impact on the brittle fracture occurrence. The condition of brittle fracture, expressed in the form of Hall-Petch equation has the following view:

$$\sigma_b = k_B d^{1/2}$$
Another form of the condition is the equation of the Griffith-Orowan-Irwin:

\[ \sigma_b = \sqrt{\frac{2\gamma_p}{E}} d, \]

where \( E \) - Young’s modulus; \( \gamma \) - fracture surfaces effective energy; \( k_B = \sqrt{\frac{2\gamma_p}{E}} \); \( d \) - the size of the structural component (grain).

The part ability to carry high load items at the lowest possible weight and deformations most fully characterized by generalized index \( \sigma 02E/j2 \), where \( j \) - density of the material [1].

Durability of parts under cyclic loading is characterized by the coefficient [8]:

\[ K_{yw} = \frac{\sigma_1}{\sigma_{max}} \]

where \( \sigma_1 \) - endurance limit at a symmetric cycle; \( \sigma_{max} \) - equivalent stress, depending on the type of load and stress state circuit parts during operation. By-turn \( \sigma_1 \) depends on \( \sigma_{02} \) and \( \sigma_{f1} \). \( \sigma_1 \) is related to the \( d \) -metalla already given in the Hall-Petch relationship.

Based on these relations it follows that for each type of fracture, causing failure, you can define the structure and related mechanical properties of the indicating parts durability during operation.

Consider the technological aspects of the formation of machine parts service properties. According to the previously given relations, parts durability stipulated by fracture failure depends primarily on the strength properties of the metal.

Strength is defined as the ability of a metal to resist irreversible (plastic) deformation when subjected to a load. Modern ideas of plastic deformation associated with its dislocations mobility. The resistance to deformation improvement can be achieved by means of the metal fine structure certain formation, retarding the motion of dislocations. Basic mechanisms of dislocations retardation are as follows:

- The formation of atoms aggregates (segregation) of alloying elements (openings) around dislocations in solid solutions;
- Increase in the dislocation density, leading to atoms interaction consolidation of near the moving dislocations. In this case, the stress field of atom interaction forces interferes in the movement of some others;
- The formation of barriers to moving dislocations in the form of interface in crystals or particles of the second hardening phase of, i.e. creation of objects inside the alloy with different crystallography of dislocation slip.

The technological parts processing route has a decisive influence on the formation of optimal structural states of the metal and the corresponding strength parameters. Schematic diagram of the formation of service properties in the system of the metal into the part transformation is shown in Fig. 2, where

Su - basic properties of the material; Sc - service properties of parts; a, d- processing routes with indirect influence of plastic forming technology (PFT) to Sc; c, e - processing routes with direct influence of PFT on Sc; d, e - processing routes without influence TPF on Sc; N - normalization; TI – thermo-improvement; RA – recrystallization annealing; DA - diffused annealing; SpA - spheroidizing annealing; SA - softening annealing; PSA - pearlite structure annealing; LGA - large grains annealing; QT - quenching + tempering; ChHT - chemical heat treatment; FO - physical treatment (laser, plasmic, etc.); ThCT - thermo cyclic treatment; CF - cold forging; LTMTF and HTMTF - stamping in low-and high-temperature thermomechanical treatment mode; HSS- high speed stamping; SES – stamping in superelastic conditions; HF - hot forging; IThF - isothermal forging.

Change metal properties in the process of transforming it into a piece should be analyzed by taking into account the technological heredity. Metal structure and properties depend not only on the
finishing, but the features of all the preceding processes starting with the step of melting the metal on
the operating step 1 up to acquisition workpieces on steps 2, 3, 4, 5.

Carriers of hereditary information are chemical composition, material structure and connected with it
mechanical and other properties. To achieve high performance of metal components properties it is
necessary to take into consideration or better – to manage technological inheritance. Those properties,
which positively affecting the quality of parts, must be maintained and developed, as for negative
characteristics, it is desirable to eliminate them at the initial stages of treatment.
Influence of certain technological treatment route on the metal properties change should be assessed in terms of inheritance coefficients [9]:

\[ K_c = \frac{C_{i+1}}{C_i}, \]

Where \( C_i, C_{i+1} \) - respectively, the values of some properties before and after exposure to the metal. Inheritance coefficients characterize changes in the properties at this stage of processing their values relative to the preceding stage. The value of \( K_c = 1 \) indicates that the \( i \)-e property is inherited without change, when \( K_c > 1 \) – property value increases, and when \( K_c < 1 \) decreases.

| Type of aggregative technological [4] | Type of semi finished work piece for producing a detail | Mechanical properties of parts | KCV, kilojoule/m² | δ, % | Ψ, % |
|--------------------------------------|--------------------------------------------------------|------------------------------|------------------|------|------|
| BI                                   | Molding in sand-clayey mould                           | \( \sigma_1 \), MPascal       | 186              | I    | I    |
|                                      |                                                        | \( \sigma_{02} \), MPascal    | 320              | 1,1  | 20   |
|                                      |                                                        | \( \sigma_B \), MPascal       | 69               | 1,35 | 1/18 |
|                                      |                                                        | \( KCV \)                      | 75               | 1,8  | 1,8  |
|                                      |                                                        | \( \delta \)                    | 20               | 1,6  | 1,6  |
|                                      |                                                        | \( \Psi \)                      | 36               | 1,8  | 1,8  |
| BII                                  | Profiled iron (normalization)                          | \( \sigma_1 \), MPascal       | 1,4              | 2,03 | 2,7  |
|                                      |                                                        | \( \sigma_{02} \), MPascal    | 320              | 1,1  | 1,1  |
|                                      |                                                        | \( \sigma_B \), MPascal       | 685              | 1,1  | 1,1  |
|                                      |                                                        | \( KCV \)                      | 75               | 1,37 | 1,37 |
|                                      |                                                        | \( \delta \)                    | 17,6             | 1,6  | 1,6  |
|                                      |                                                        | \( \Psi \)                      | 36               | 1,8  | 1,8  |
| BIII                                 | Forging from a cast form (normalization)               | \( \sigma_1 \), MPascal       | 260              | 1,1  | 1,1  |
|                                      |                                                        | \( \sigma_{02} \), MPascal    | 320              | 1,1  | 1,1  |
|                                      |                                                        | \( \sigma_B \), MPascal       | 685              | 1,1  | 1,1  |
|                                      |                                                        | \( KCV \)                      | 75               | 1,37 | 1,37 |
|                                      |                                                        | \( \delta \)                    | 17,6             | 1,6  | 1,6  |
|                                      |                                                        | \( \Psi \)                      | 36               | 1,8  | 1,8  |
| BIV                                  | Forging from profiled iron (normalization)             | \( \sigma_1 \), MPascal       | 379              | 1,17 | 1,17 |
|                                      |                                                        | \( \sigma_{02} \), MPascal    | 455              | 1,13 | 1,13 |
|                                      |                                                        | \( \sigma_B \), MPascal       | 866              | 1,13 | 1,13 |
|                                      |                                                        | \( KCV \)                      | 83               | 1,5  | 1,5  |
|                                      |                                                        | \( \delta \)                    | 2,7              | 2,7  | 2,7  |
|                                      |                                                        | \( \Psi \)                      | 2,7              | 2,7  | 2,7  |

Ci - the numerator - the average absolute value of the metal parts properties; 
K - the denominator - the coefficient of inheritance with respect to the properties of the metal part Ci obtained by crystallization of the melt in the sand-clayey mould.

\[ K = \frac{C_2}{C_1} \]

Parts manufacturing process route significantly affects the mechanical properties of the metal. Table 1 presents a comparison of mechanical properties of metal parts made according to different processing routes. Data are presented for widely used structural steel 40X and averaged with the anisotropy of properties.

A higher level of parts mechanical properties produced by TCB BII, III, IV with using plastic deformation depends on special influence of the latter on the specific micro-and macrostructure of cast metal. Properly set plastic deformation modes promote to eliminate porosity of cast structure; to weld
Macroddefects like cracks, crushing and rational orientation of nonmetallic inclusions; redistribution of liquidation zones, forming a fibrous texture and deformation structure, grinding of sub- and macrograin, carbide constituent breakage and carbide inhomogeneity decrease and the like. [10]

Higher values of the metal strengthening characteristics can be achieved by deforming the metal while producing parts in the modes of low (LTMTF) and high (HTMTF) - temperatures of thermomechanical treatment. Data on the effect of various kinds of thermal and thermomechanical treatment on the strength and plastic properties of steel 30KhGSA are shown in Table 2.

Modes 3 and 4 (Table 2) by its temperature and speed settings ensure the passage of hot deformation in a deformed austenite dynamic polygonization process. At the optimal crank-type presses of deformation speed mode is not provided, so the strengthening properties of the metal forgings produced with this type of equipment in HTMTF mode are lower (Mode 8, Table 2) than those which can potentially be achieved.

Metal hardness and strengthening characteristics increase after HTMTF complicates subsequent machining process of forgings. Therefore, applying HTMTF at die forging is advisable if, as a result of stamping is possible to obtain the finished part or final shaping can be accomplished in the processes (grinding, electrochemical machining, etc.), which are not associated with non-blade processing.

### Table 2

Comparison of metal parts mechanical properties produced by plastic deformation at various forming and heat treatment modes (30 HGSA steel material)

| № п/п | Forming and heat treatment modes | Mechanical metal properties |
|-------|---------------------------------|----------------------------|
|       |                                 | σ₁, MPascal | σ₀₂, MPascal | σₘ, MPascal | KCV, Kjoule/m² | σ, % | Ψ, % |
| 1     | Cold deformation (relational deformation 60%) | 560 | 1100 | 1200 | 75 | 3 | 18 |
| 2     | Cold deformation + tempering 300°C + high speed annealing + tempering 300°C (preliminary thermal treatment PTMT) | 1200 | 1640 | 1860 | 200 | 9 | 30 |
| 3     | Half-hot deformation at low temperature thermomechanical treatment mode (LTMTF) | 1890 | 2200 | 2700 | 400 | 7 | 25 |
| 4     | Hot deformation at high-temperature thermomechanical treatment mode (HTMTF) | 1760 | 2000 | 2400 | 500 | 10 | 35 |
| 5     | Hot deformation + hardening with forming temperature + tempering 300°C (TMTF) | 1490 | 1680 | 1910 | 250 | 10 | 30 |
| 6     | Hot deformation + thermo-improving | 930 | 1410 | 1690 | 185 | 10 | 25 |
| 7     | Hot deformation + normalization | 450 | 550 | 815 | 314 | 21 | 62 |
| 8     | Hot deformation + - thermo cyclic treatment 14-15 cycles (ThCT) | 409 | 92 | 550 | 314 | 21 | 62 |
Mechanical properties are averaged taking into account the anisotropy: in the numerator - the absolute values of the properties, the denominator - inheritance coefficient $K$ after thermomechanical treatment.

Thus, the choice of a rational thermomechanical plastic deformation mode can purposefully change the properties of components, improving their service characteristics, particularly durability.

3. References
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