Effect of steel structure and defects on reliability of parts of impact mechanisms

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Abstract. The paper discusses selection of materials suitable for manufacturing critical parts of impact mechanisms. It is shown that in order to extend life of parts exposed to high dynamic loading, it is expedient to use medium- and high-carbon alloy-treated steels featuring low impurity with nonmetallic inclusions and high hardening characteristics. Application of thermally untreated parts is undesirable as steel having ferrite–pearlite structure possesses low fatigue strength. Aimed to ensure high reliability of parts with a hardness of 42–55 HRC, steel should be reinforced by thermal treatment with the formation of multicomponent martensite–bainite structure. High-quality production should include defectoscopy and incoming material control.

Extension of service life of impact machines is a complex task. Early failure of parts can be the result of engineering errors, or disregard of technology of manufacture and operation of the machines. One of the main causes of early failure of impact mechanism parts is the improper selection of material. Parts of impact machines should possess a set of properties, among which the critical characteristics are strength, hardness, impact toughness, crack and wear resistance [1]. Generally, an increase in hardness and strength of steel decreases its impact hardness and fatigue failure strength; for this reason, the main objective of equipment design is rational selection of materials and creation of a structure capable to ensure optimal combination of the above-listed properties (Figure 1).

![Figure 1. Correlation of the main properties and structure of steel.](image-url)
Practically, the choice of steel for manufacturing different parts is governed by many factors: operating conditions and target life of mining machines, economic efficiency, availability of wanted roll stock, etc. Which steel should be used—cheap alloy-free or expensive alloyed—is a question of individual choice; however, it is desirable to manufacture parts of impact machines from medium- and high-carbon alloy-treated steels with high hardenability for thermal treatment. This condition is obligatory for critical parts subjected to cyclic or dynamic loading.

![Figure 2](image1.png)

Figure 2. Fatigue life of steel 45: 1—general endurance; 2—initiation of fatigue cracks.

Figure 2 depicts tests data on fatigue life of steel 45 specimens subjected to multiple dynamic compression [2]. If steel after quenching and tempering has hardness less than 30 HRC, its endurance is low and weakly depend on the hardness level (zone I in Figure 2). In medium-carbon steel with the structural hardness from 35 to 55 HRC, endurance grows together with the strength characteristics (zone II). Generation of low-temperature tempered martensite structure with high level of internal stresses in steel decreases steel endurance due to drop in the length of stage of fatigue crack initiation and growth (zone III). An optimal combination of strength and fatigue resistance is a feature of steel having disperse structure of fine pearlite. Steel with ferrite–pearlite structure weakly resists fatigue failure. Fatigue cracks rapidly grow towards interfaces of ferrite and cementite plates, which result in quick breakdown of parts with the formation of brittle fracture surfaces (Figure 3). The use of steel possessing high hardenability reduces portion of ferrite–pearlite structure in the total volume of hardened parts and allows higher strength of steel at the simultaneous increase in the steel crack resistance.

![Figure 3](image2.png)

Figure 3. Steel 45 fracture surface: (a) brittle fracture of air-hardened steel ($\sigma_{\text{endur}}=627$ MPa, $K_{\text{CU}}=76$ J/cm$^2$); (b) ductile fracture of quenched and high-tempered steel ($\sigma_{\text{endur}}=780$ MPa, $K_{\text{CU}}=118$ J/cm$^2$).

It is noteworthy that optimization of steel structure at the stage of experimental development is not a guarantee of high performance of mining machines of mass production. Expert appraisal of steel quality and the analysis of failure causes in machine parts undertaken at the Destructive Testing Laboratory of
the Novosibirsk State Technical University point at the tendency toward degradation of rolled steel of large thickness and diameters. Iron plates thicker than 20 mm, rolled and forged products having diameters larger than 200 mm may contain very many internal defects. Sometimes there are cracks up to a few millimeters long (Figure 4). For this reason, in order to ensure high reliability of products, machine-building plants should accomplish incoming inspection of rolled metals.

Figure 4. Cracks in (a) forged steel 20X24A and (b) Ø 250 rolled steel 45.

Another aspect of concern during manufacture of mining machine parts is high content of nonmetallic inclusions in steel (Figure 5). High impurity with nonmetallic inclusions in steel is explained by overwear of metallurgical equipment and general degradation in steel production culture since most of metallurgical plants produce construction steels for which impurity is not a critical factor. Low performance characteristics of steel with the high content of inclusions are conditioned by the fact that the external loading results in the localization of internal stresses at the inclusions, which initiates fast fatigue cracking. Furthermore, diffusion processes at the inclusions alter chemical composition and strength characteristics of steel, whereas different coefficients of thermal expansion of an inclusion and basic metal induce extra thermal stresses. Production of pure steel free from nonmetallic inclusions is an expensive process. Practically, it seem more important not to minimize the impurity due to nonmetallic inclusions but to produce steel containing inclusions of a certain type, shape, size and morphology so that to affect properties and performance of steel minimally.

Figure 5. Nonmetallic inclusions in steel 45 in the form of (a) points and (b) strings.

The experiments carried out at the Novosibirsk State Technical University prove that the presence of large inclusions in steel results in the decrease in life of critical parts of impact machines by 2 times and more [2–4]. Statistics shows that the inclusions exert very high aggravating effect on fatigue endurance of highly strong steels. In this case, up to 70% of fatigue cracks causing failure are initiated by nonmetallic inclusions. Under low-cycle loading (target life of parts is less than $10^5$ cycles), when specific loads are close to the yield point of steel, the main source of fatigue failure is not the inclusions but surface defects; for this reason, for parts intended for operation under static or low-cycle
loading, impurity of steel due to nonmetallic inclusions is not critical. Thus, for manufacturing parts for long service life (more than $10^7$) under loading, it is recommended to use steels with the inclusions of small size (less than 20 μm) and low content (not higher than the second number in the scale by State Standard GOST 1778-70). In case of cyclic tensile or alternating loading, the most critical parameters are the size and shape of inclusions (small size and spherical shape are preferred) while their morphology (or chemical composition) has no significant influence on fatigue endurance of steel. For parts meant for operation under dynamic compression, high durability can be ensured using steel having hard inclusions [4]. Inclusions highly affect performance of parts in aggressive media when corrosion processes intensify initiation and growth of fatigue cracks (Figure 6) [5]. Unfortunately, Russian standards have no regulations on content of inclusions in structural alloy-treated rolled steel. In this case, mining machine building plants would maintain high quality of manufactured parts by placing special requirements on impurity of steel due to nonmetallic inclusions (not higher than the second number in the scale), specifying these requirements in steel delivery contracts and by undertaking verification checks of rolled steel in accordance with the State Standards GOSR 1778-70: Steel. Metalographic analysis of nonmetallic inclusions.

![Figure 6](image6.png)

**Figure 6.** Fatigue endurance of steel 45: 1—air tests; 2—water tests.

High reliability and endurance of impact mechanism parts subjected to loading can be ensured using new advanced methods of thermal treatment and generation of multicomponent super-strong steel having high fracture toughness. As a rule, such methods are based on formation of mixed structure consisted of regulated amount of martensite, bainite and residual austenite [6–12]. Figure 7 depicts one of the treatment cycles. Thermal treatment generates gradient structure in steel (Figure 8). Martensite ensures high strength characteristics while bainite and austenite have high fracture toughness. Comparing to conventional tempering technology, the proposed thermal treatment approach provides a double increase in impact toughness and a triple increase in fatigue endurance of steel at the similar strength level.

![Figure 7](image7.png)

**Figure 7.** Thermal treatment and formation of martensite–bainite structure.
Another promising way of enhancing reliability and endurance of parts of impact mechanisms is application of new nano-structured bainitic steel possessing high strength and fracture toughness [13, 14]. New-generation nano-structured bainitic steel contains: carbon 0.8–1.2%; silicon 1.5–2%; manganese 1.5–2% and chromium 1.5–2%; they also can be additionally alloyed with cobalt, molybdenum and aluminium. Thermal treatment circuit of such steel includes heating up to austenite transformation temperature, subsequent accelerated cooling down to a temperature 5–10 degrees higher than martensite transformation temperature and, then, long isothermal ageing in a chamber furnace under the same temperature for a few hours. The resultant steel has a structure consisted of nano-bainite and residual austenite, possessing high strength (up to 2300 MPa), high fracture toughness (to 30 MPa·√m) and plasticity (to 20%). It should be mentioned that thermal treatment methods include accelerated cooling down to a temperature of 150–300°C and, thus, require purchasing low-temperature salt-bath furnaces.

Conclusions
1. Depending on basic criteria laid on a material, different types of thermal reinforcement should be used. Low tempering allows production of highly strong steel (hardness higher than 52 HRC). High-hardness steel (42–52 HRC) can be reinforced by thermal treatment with mixed austenite transformation. Isothermal quenching with the formation of lower bainite ensures optimal combination of fracture toughness and strength in 38–42 HRC steel.
2. It is undesirable to use thermally untreated parts as ferrite–pearlite steel has low fatigue resistance. It is inexpedient to carry out thermal treatment of steel if brittle structure of low-tempered martensite with the hardness higher than HRC 55 is formed.
3. Nonmetallic inclusions in steel appreciably decrease its fatigue endurance. They are affect badly especially on high-strength steel parts exposed to multi-cycle loading. In low-strength parts under static or low-cycle loading, impurity of steel with nonmetallic inclusions is not a critical factor.
4. In order to provide high-quality production, machine building plants should carry out defectoscopy and incoming inspection of delivered rolled steel.

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