

# *Effect of Technological Defects on Reliability of Engineering Products*

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**Abstract**—The nature and reasons of two cases of premature failure of engineering products are investigated (metal-composite cylinder for moto fuel and metal rod of bulldozer's hydraulic cylinder). By methods of metallography and fractography with using the basic provisions of metallurgy, physics of metals, physics of strength and fracture we have identified the localization of initial cracks, the micromechanisms of their formation and subsequent development, and described the general picture of failure. It is shown that the main physical and mechanical causes of cylinder's failure are connected with coarsening and heterogeneity of intermetallic phase distribution in an alloy and the increased roughness of internal surface processing on the metal liner. It is established that the reason of the rod failure was unsatisfactory quality of metal caused by errors of heat treatment before chrome plating. As a result, there are structural inhomogeneities (ferritic banding, non-metallic inclusions) in the hardened layer and in the transitional zone to the core area which initiated the fatigue cracks. The main mechanism of failure of the automobile gas tank and bulldozer's hydraulic-cylinder rod is metal fatigue that evolves in time and is induced by manufacturing processes errors.

**Keywords**—*automobile gas cylinder; bulldozer; service fracture; technological defects; fatigue cracks*

## I. INTRODUCTION

Despite progress in developing the approaches to constructional design, manufacture, diagnosis of various technical objects, quite often there are their failures, accidents and catastrophic destructions. Research of reasons causing damage of component parts on machinery and equipment allows not only identifying initial zones, nature, sequence of destruction processes, but it is also the scientific basis for improving the design characteristics and advancement in manufacturing technologies of engineering products and structures. To identify the causes of destruction of machine parts and structural elements the methods of fracture diagnostics are applied. They include a set of studies using

fractography, metallography, x-ray diffraction analysis, mechanical tests taking into account the general laws of deformation and fracture processes of materials at different scale levels [1-4]. The fracture surfaces represent a direct result of material discontinuous, identify the weakest points of parts, and contain information of nature, features and causes of destruction. Thus, the study of the causes of parts destruction taking into account material structure, properties and operating conditions is an urgent task. Besides, the data obtained are important for improving the reliability and working capacity of engineering products under various operating conditions. The object of this paper is to identify methods of fracture diagnostics, the nature and causes of premature destruction of an automobile gas cylinder and a rod of bulldozer's hydraulic cylinder.

## II. RESEARCH METHODS AND RESEARCH EQUIPMENT

At the first stage research carried out with the existing fragments of emergency facilities were visually examined according to the general standard recommendation. The purpose of a visual survey is to identify the features of macro-construction fractures, the overall picture of structural failure, damage to internal and external surfaces, and to determine the most appropriate areas of cutting samples for further study and implementation of mechanical test.

To determine the chemical composition of metal of a cylinder, a bulldozer's stock "Foundry-master UVR" spectrometer was used. Metallographic and fractographic studies on the devices "Neofot-32", "Axio Observer D1m", Altami PSO745-T, "Stemi 2000C", "JEOL JSM-6480LV" were carried out.

Microdistribution of chemical elements in the structural components of metal has been investigated by the method of electron microprobe analysis in scanning of the slot with the JEOL JSM-6480LV device (the beam diameter ~2 mkm, K<sub>α</sub>-radiation).

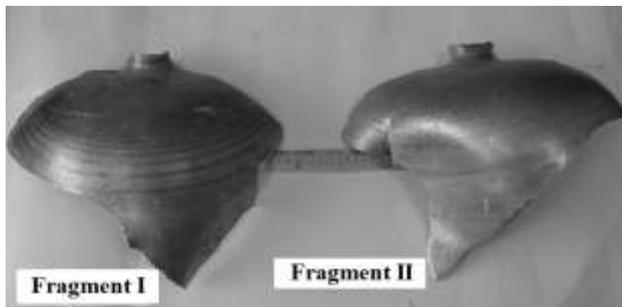
Tension tests are performed at room temperature by “Zwick/Roell Z600” test machine. Brinell hardness measurements are carried out on “Heckert” hardness tester.

### III. MAIN RESULTS AND DISCUSSION

#### A. Destruction of cylinder for automotive fuel gas

The emergency fragmental rupture of gas fuel cylinder had occurred in summer in the garage box shortly after fillings. The cylinder was torn apart with the separation of the bottom of inner metal shell (liner) from the side of a plug, dividing the bottom into several parts and removing of the outer composite shell (Fig. 1). Fragments of the emergency cylinder liner were heavily deformed. On the liner inner surface the visible corrosion defects such as pits and blowholes were not revealed.

The inner metal shell and the outer fiberglass shell of metal-composite cylinders must take the load as one, and in emergency cases they should be destroyed at the same time, fully realizing its joint strength. In addition, the presence of firmly adjacent fiberglass shell usually excludes the fragmental type of cylinders fracture. In this regard the comminuted type of cylinder ruptures in this case indicates the loss of strength of the power shell and its adhesion with the metal at the final destruction time.



a

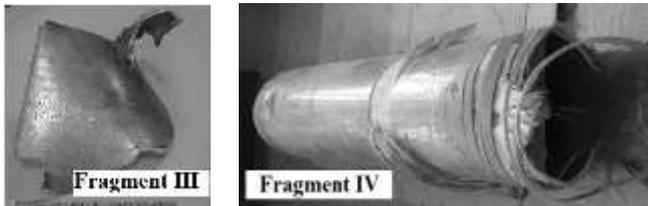


Fig. 1. General view of the emergency liner fragments: a, b - fragments of the lower part; c - upper part on the side of valve with preserved composite shell

The metal of liner meets the required standards on the deformable aluminum AA 6061 alloy. The hardness of metal in the intact area corresponds to regulatory requirement. However, the hardness of decayed bottom has a reduced value (837.7 MPa at standard requirement of 864.2 MPa).

Macrofractographic features of fracture allowed determining that the cylinder destruction had begun from its inner surface on the side of a plug (Fig. 2, a). In zone 1 the

shiny surface of focal fatigue crack is clearly visible (Fig. 2, c). In zone 2 the focal crack is a narrow and also lapped areas (Fig. 2, b). The important feature of inner surface of the liner fragments I and II is the cracking of different length (up to 19 mm) and different degree of disclosures (up to 0.47 mm), which are mostly near the neck thread (Fig. 2, d). The maximum depth of their penetration into metal is  $\approx 1.1$  mm.

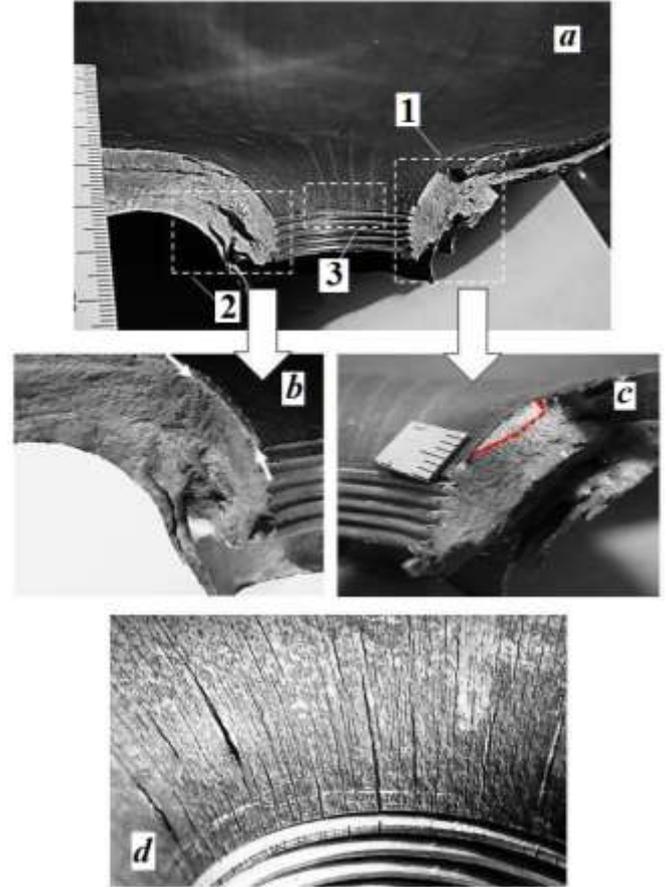


Fig. 2. General view of the failed filler neck (a) and the enlarged images of fracture zones 2 (b), 1 (c) and section 3 (d); light strip between arrows (b) and light area bounded by a dotted line (c) – surface of focal fatigue cracks.

Aluminum liners of composite high-pressure cylinders from heat-treatable aluminum alloys on the base of the Al–Mg–Si system (Avials) after manufacturing (spinning) are subjected to heat treatment (quenching and artificial aging) in order to provide the required level of strength [5-7]. During heating for quenching, the hardening excess phases dissolve. When quenching, these phases do not have time to stand out, as a result, a supersaturated solid solution of alloying elements in aluminum is fixed. When aging of the hardened alloy depending on temperature and duration of the process in supersaturated solid solution we can see the sites enriched with alloying elements (Guineau-Preston zones) and dispersed decay products – particles of intermediate metastable and stable phases are formed in the supersaturated solid solution. The hardening of the alloy occurs due to the formation of supersaturated solution during quenching and, mainly, during

aging at the stages of formation of Guinier-Preston zones and dispersion hardening (the main strengthening phase in Avials is the allocation of dispersed particles of  $Mg_2Si$ ).

The alloy from which the failed cylinder had been made is characterized by heterogeneous structure with enlarged particles of the reinforcing intermetallic phase. These shortcomings of structure are more defined in the decayed bottom (Fig. 3, *b*). The particle coarsening led to the decrease in their number, increased the distance between them and contributed to the decrease in hardness. The brittleness of intermetallic compounds worsened the resistance of material to nucleation and propagation of fracture.

The cracks initiation had occurred on cracking of inner surface of the bottom. The surface of focal fatigue cracks has a typical cascade structure and contains a set of intermetallic compounds particles (Fig. 3, *c*).

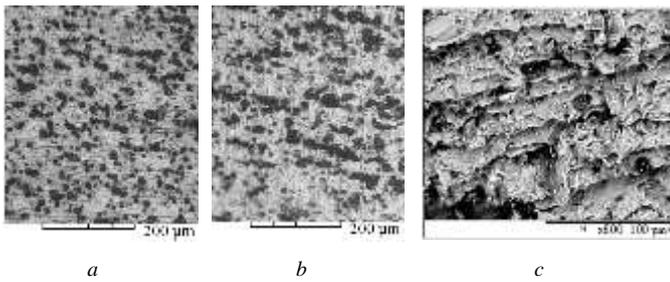


Fig. 3. Metal microstructure of the decayed cylinder in the undamaged cylindrical part (*a*), in the zone of destruction (*b*) and microstructure of focal fatigue cracks in zone 1 (see Fig. 2, *a*)

According to the results of the studies, the main physical and mechanical cause of the cylinder liner destruction long before the wearing of designed life is the unsatisfactory structure of a material. Isolation of the hardening phase in the form of conglomerates of enlarged brittle particles of intermetallic compounds, their uneven distribution with weakly expressed linearity reduced the hardness value. The reduced hardness of a material caused the increased roughness of the liner inner surface. This led to the creation of a system of surface stress microconcentrators. In the zone of lower bottom neck on the stress microconcentrators under the action of operational loads arose the primary shatterings of the metal which had been already weakened by the relatively large allocations of fragile intermetallic phases.

In conditions of low-cycle loading on primary shatterings focal fatigue cracks were born. Since fatigue is a process developing in time, the destruction of the cylinder did not appear simultaneously, and had two major phases. At the first stage there were processes of nucleation and propagation of fatigue cracks until one of them with advanced development had reached a critical value. This brought the process to a stage of the final destruction with a dynamic nature. The stage had been realized through the formation of a system of ductile cracks with their subsequent confluence, formation and throwing of fragments.

The beginning moment of the cylinder avalanche destruction depended on two factors: the ability of metal liner to plastic deformation without loss of its stable character and the rate of destruction and increase of instability of the outer composite shell restraining the expansion of the liner, causing the accumulation of elastic energy throughout the system.

The level of strength and plastic properties of metal liner, as well as the deterrent effect of fiberglass outer shell provided quite a long period of time from the appearance of fatigue cracks prior to the development of the critical local strain in the liner. These deformations were transferred to the outer shell causing its progressive destruction. After the loss of functional properties of the force shell, the metal liner assumed the entire load; the stage of its deformation began with an uncontrolled speed and subsequent fragmentation destruction with the release of a large reserve of accumulated elastic energy. It is also clear that the achievement of the critical state of the cylinder had the largest probability after gas refueling.

### B. Destruction of a rod of the bulldozer hydraulic cylinder

The emergency failure of the left rod of a bulldozer hydraulic cylinder happened after a minor operating time during 550 motor hours while performing the works (pushing of open peats). Ambient temperature at the moment of breakage was  $-25\text{ }^{\circ}\text{C}$ . The fracture occurred at distance of  $\approx 256\text{ mm}$  from the rod lower end (Fig. 4, *a*). The rod diameter is  $76.15\text{ mm}$ ; the original length is  $182.3\text{ mm}$ .

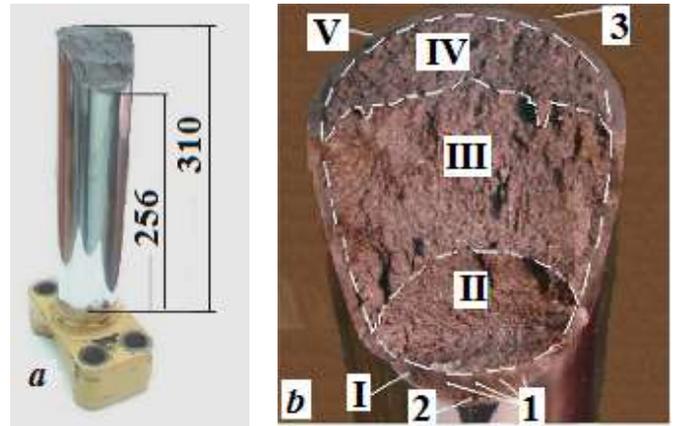


Fig. 4. General view (*a*) and fracture surface of a rod short fragment (*b*). I, II, III and IV are fracture areas; 1 – the place of the destruction nucleation; 2 – lapped areas; 3 – cracking from the outer surfaces

According to the spectral analysis, the emergency rod had been made of high quality carbon steel, and after surface quenching it was hardened with chrome coating. The thickness of the chrome layer, the depth of a hardened layer and its hardness reflect quality requirements.

Rods of hydraulic cylinders of working equipment of excavating and transporting machines refer to the power elements operating at alternating loads under severe conditions

of environmental influence. Because of the immediate proximity to the working bodies of the machine, dust and contamination, the abrasive action of particles skidded from the external environment; the rods are exposed to corrosion and other damages during operation. Damage of the rods working surface reduces their strength, especially fatigue. Therefore, to ensure high performance different technologies for hardening rods are used including electrolytic chrome plating. Wear-resistant chrome coatings allow repeatedly increasing the service life of parts at work on friction, as well as make it possible to use cheaper carbon steel for their manufacturing instead of alloy steels.

However, chromium plating can significantly reduce the fatigue strength of details (including low-cycle), in particular due to such phenomena as a steel hydrogenation and the occurrence of residual stresses. Hard carbon steels and structural steels of higher strength have the greatest reduction of fatigue limit. Therefore, to obtain high-quality coatings from chromium a broad range of technological processes and special events, including preliminary preparation of parts, subsequent processing of the obtained coatings, their control is used [8,9].

A visual study of the fracture reveals several sites that different in appearance of macro-relief and roughness (Fig. 4, *b*). Fracture focuses are in the subsurface layer (Fig. 4, *b*, zone I, arrows 1). Zone I consists of smooth slightly convex areas and is located near the rod surface at a depth of  $\approx 3$  mm. In areas of focal cracks distribution there are scars arising from the merger of adjacent cracks; also in zone I, the bow-shaped lapping of a surface is clearly visible (arrow 2 in Fig. 4, *b*), formed at the friction of crack faces during the time interval from the moment of its formation to the final destruction of a part.

The study of the focus of destruction on an electron microscope revealed the presence on their surface the multiple non-metallic inclusions, mainly related to oxygen containing. It is obvious that they played a significant role in the origin of the initial micro cracks and the implementation of micromechanism of low-energy grain boundary destructions. The accelerated development of destruction was also caused by brittle transcrystalline cleavages. The initial defects formed by the cracking and cleaving subsequently extended by the mechanism of fatigue with the formation of characteristic fatigue striations (Fig.5). As a result of the merger of several fatigue cracks, the front of the general crack was formed. Its exit to the surface weakened the section of a part, but not to a critical level. This is evidenced by the lapping of the crack faces with the formation of an arc-shaped shiny surface: the stronger the lapping is, the lower the crack growth rate is and, accordingly, overload. No overload is also evident due to a small height of scars in the focal area.

Reduction of the rod working section due to the appearance of cracks over time led to the appearance of the cracking from the outer surface on the opposite side of the rod

(arrow 3 in Fig. 4, *b*). The direction of the chevron marking of brittle fracture that framed the rod fracture (zone V, Fig. 4, *b*),

characteristic of features and a high level of relief allow defining zones II, III, IV as zones of final rupture.

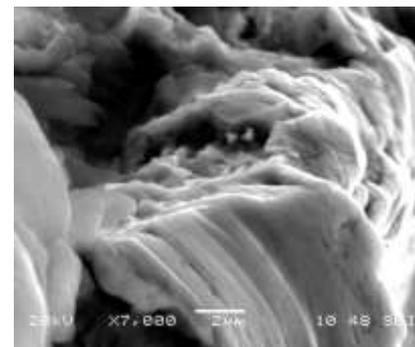
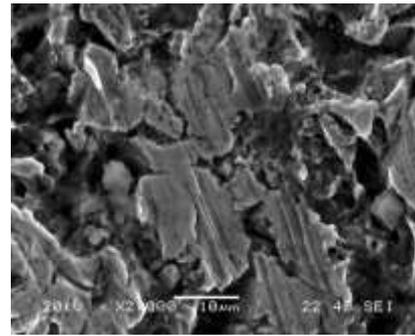


Fig. 5. The sites of fracture with fatigue striations

In the microstructure of the cross section of the rod, there are several zones: chrome coating, a zone hardened to a depth of 3 mm, intermediate zone and base metal. A great influence on the quality of chrome plating has such an operation of pre-preparation of rods as a heat treatment. As the chrome coatings are needed to be deposited on a sufficiently solid foundation, the investigated rod was subjected to quenching with the use of high frequency currents before chroming. The detail study revealed the presence of structural defects in the quenching zone and the transition zone from the hardened layer to the core. These are the single and banded structure formations which are the selection of ferrite interspersed with carbide particles (Fig. 6, *a*, *b*). The presence of such "soft" decarburized zones with reduced strength is particularly dangerous in the transition zone which is confirmed by the origin of fatigue cracks in this area.

One of the causes of ferrite banding is the presence of plastic sulfide inclusions in the steel structure. The microstructure analysis of a transition layer and a core revealed a significant number of non-metallic inclusions with various size and origin (Fig. 7, *a*). According to data of the electron microprobe it has been identified that non-metallic inclusions really have mainly sulfide and also oxygen origin (manganese sulfides, simple oxides, oxysulfides), and also silicates (Fig. 7, *b*).

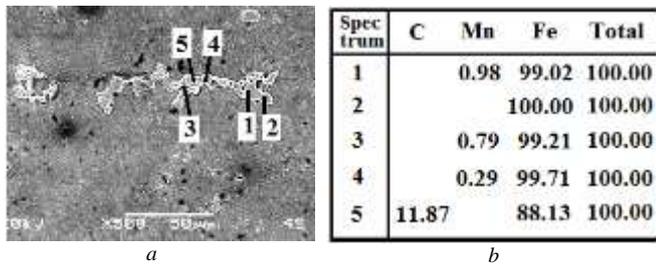


Fig. 6. The microstructure of a rod metal: *a* – banded ferrite formations; *b* – micro-distribution of chemical elements in ferrite formations.

According to the literature, the pollution by sulfides, their form and morphology are one of the most important factors determining a steel quality in terms of its operational reliability [10]. At heat treatment the fine sulfides can stand out on the boundaries of austenite grains causing the origin of intergranular fracture. In addition, as we have noted earlier, the sulfides in heat treatment can contribute to the occurrence of ferrite sites with reduced strength that especially dangerous in the case of banded-line form of such phases.

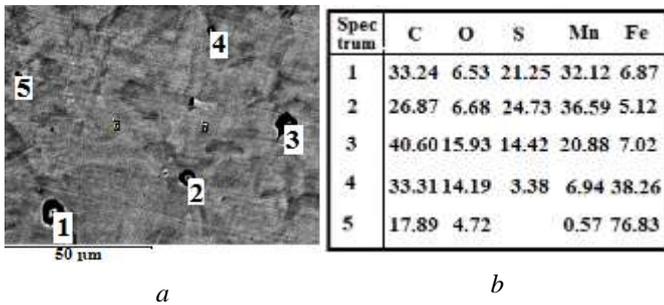


Fig. 7. Non-metallic inclusions in the transition zone (*a*) and the chemical composition of non-metallic inclusions (*b*)

Destruction of the hydraulic cylinder rod of a bulldozer is initiated by structural heterogeneity (ferrite banding, multiple nonmetallic inclusions) in the tempered layer and in the zone transitional to a rod core. Simultaneous initiation of several initial cracks (rather than propagation of a single crack from one random stress concentrator) indicates the systemic nature of the negative impact of the near-surface structural factors causes the destruction. This is confirmed by the localization of all fatigue failure foci at the site of the transition from the quenching zone to the rod metal core. Further development of initial micro cracks occurred due the mechanism of fatigue. Final destruction is brittle.

The coincidence of the sites depth of localization of the initial micro cracks with the hardened layer thickness, the presence of multiple non-metallic particles on their surface, the formation of a brittle chevron marks with a thickness equal to the thickness of a hardened layer, indicate that the

technological errors at the stage of heat treatment for chromium plating were the cause of the rod breakage.

#### IV. CONCLUSIONS AND RECOMMENDATIONS

Analysis of unacceptable failures of technical products, their elements and parts shows that the reasons are mainly determined by two factors – wrong methods of operation and errors of manufacturing processes. The investigated cases of emergency destruction were caused by hidden defects of a structure. The main reasons for the catastrophic destruction of an automobile gas cylinder are connected with the coarsening and heterogeneity of the distribution of the intermetallic phase in the aluminum alloy from which the liner was made. The main reason for the breakdown of the bulldozer rod is the presence of structural defects in the quenching zone and in the transition zone from the hardened layer to the core. The primary cracking was initiated at sites with ferrite banding and non-metallic inclusions. The described defects of the metal structure served as the stress microconcentrators. In the process of operational loads exposure these stresses initiated fatigue cracks. Despite the suddenness, presented examples of destruction are gradual failures, as caused by not external reasons but the developing of technological defects. The considered cases of accidents confirm that the basis for ensuring the reliability and safety of various engineering facilities is first of all the organization of technological and technical control.

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