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DEGRADATION OF THE SHAFT SURFACE DURING MACHINING TECHNOLOGY

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Abstract: *Estimation of structures life and ensure their safety and integrity is an essential part of the design of equipment for transport, engineering and other industries. Usually, fatal accident occurs often under varying loads without causing changes shape. Application of fracture mechanics and testing is possible to describe the propagation of cracks but the kinetics of damage in the early stages has not yet been expressed. The paper deals with identifying the causes of surface failure of a shaft made of material 42CrMoS4. On the basis of microstructural analysis completed by hardness testing, the occurrence of undesirable phases, such as non-metallic inclusions in the structure of the shaft, can be demonstrated. In the presence of various heterogeneous phases in the material structure, plucking of particles can occur during chip machining which leads to surface damage. In the conclusion, the authors recommend checking the starting material, which can eliminate problems that cause the degradation of the surface of the shaft. The failure of the surface causes the notch effect which initiates further failures of the material. Using highly sensitive methods for observing the surface such as scanning electron mikroskopy etc., unique data on mechanism of crack initiation were obtained. The authors present selected partial results of longitudinal studies that deal with failure mechanisms and surface materials and the formation of cracks.*

Key words: *chip machining, surface defects, non-metallic inclusions, microstructure, hardness, cracks.*

1. INTRODUCTION

A continuous crack detection testing of the shafts uncovered surface defects of semi finished products and a stereoscopic magnifier confirmed it macroscopically in designated locations. The shaft is produced by a company which belongs to the world's leading manufacturers of hydraulic systems and components for mobile working machines. Therefore, it is important to pay attention to the problems that occur during the machining operations, which may indicate a change in the quality of the finished product. The analyzed final product is shown in Fig. 1. Based on the crack detection testing, shaft defects were indicated in the central part of the semi-finished shaft and they were further observed from the macroscopic and microscopic aspects. The shaft is made of material 42CrMoS4 and is shown in Fig. 2. The research was aimed at determining the surface damage causes and identifying the kind of damage in detail. The next task was to determine the extent of the damage to the shaft and to analyze how the damage can affect the basic material.

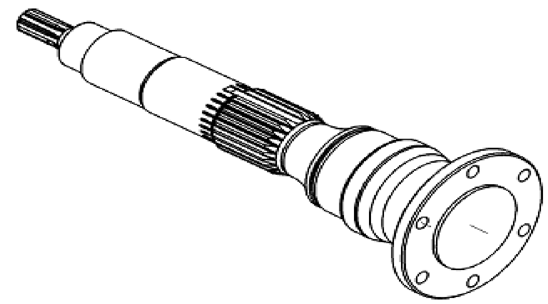

Fig. 1. Machine shaft.

Fig. 2. Damage to the shaft before further processing and hardness measurement points (1–5).

2. THEORETICAL BACKGRAUND

The occurrence of cracking is generally associated with the microstructure of the material. Metals usually crystallize in the body centred cubic system or face cen-

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tred cubic system and have a relatively large number of slip systems. These systems include planes and directions with the most densely occupied atoms [1]. Plastic deformation stimulated by mutual shear motion of densely arranged planes of atoms is relatively easy. The advantage is that the metals are capable of absorbing high amounts of energy during plastic deformation, i.e. they have high strength, as well as toughness. The barrier of plastic deformation at the crack front slows the propagation; it can even stop it. The crack is spread in the ratio of the crack driving force (work of external forces especially of the local stress tensor, strain energy of internal forces, such as contaminants, metallurgical defects, microstructural changes related to temperature, separation of contaminants to the interphase boundaries, etc.) to the resistance to crack propagation (interatomic forces and other mechanisms) [2]. According to current ideas, the life of the shaft, a body in general, given by the time at which the crack grows from the initial value l_0 to the critical length l_C at which the shaft fracture occurs. Therefore it is important to determine the dependence of the speed of propagation on external conditions (shape, load, temperature, etc.) and of course on the specific material characteristics. Theoretical determination of the local stress is generally very complicated [6], but as for the state of plane stress or deformation and particular material, the stress can be expressed, for example, by using the stress intensity factor K_I or Rice integral J for elastic materials or C^* integral for viscous materials. For these cases, we can assume the kinetic law of crack trajectory given by

$$v(X) = \frac{\mathrm{d}l}{\mathrm{d}t} = f_K(m, X)\,, \tag{1}$$

where: v − crack propagation speed, l −. crack length, f_K − kinetic function, m − material parameters for different mechanisms of wear or load, X − stress coefficient which depends on the load P, geometry of the element L, the length of the crack l and material parameters.

The critical length of the crack l_C is dependent on the achievement of critical load which can be characterized by X_C. The residual life of the shaft can then be expressed as

$$t_f = \int_{t_0}^{t_C} \frac{\mathrm{d}l}{f_k\left[X(P,l,L,m)\right]}\,. \tag{2}$$

Load variable can be determined by phenomenological relationship

$$C^* = \frac{\varepsilon_C{}'(\sigma_{ref}, \varepsilon_C)}{\sigma_{ref}} \kappa K_I^2\,, \tag{3}$$

where: $\varepsilon_C{}'$ − effective flow velocity at the reference stress $\sigma_{ref} = P\dfrac{\sigma_K}{P_K}$, κ − coefficient of plane strain or stress (strain $\kappa = 0.75$, stress $\kappa = 1$), P − load, P_K − critical load which corresponds to the critical stress y_K.

The values of the load variable X as well as the initial and critical crack length in the integration limits only apply to the specific real shaft (body), the kinetic function f_K can be determined in the laboratory. The credibility of information on the life t_f relates to the mentioned assumptions about the properties and behaviour of the particular material and especially to the reliability of the data needed to calculate the equation (2). For materials where a priori defects or other stress raisers are present, the fracture stress up to a certain temperature (called zero-temperature toughness) is lower than the yield strength. The fatigue limit depends on the quality of the surface, concentration of stress in the surface layers induced by surface indentations-defects and on the overall size of the body [4].

3. EXPERIMENT

The first step of the experimental process was the assessment of the basic material from which the shafts are manufactured. The starting material showed the occurrence of discontinuities which were subjected to metallographic analysis [3], Fig. 3.

3.1. Properties of steel 42CrMoS4

The shafts are made of low-alloy high-grade chrome-molybdenum steel; it is steel with high hardenability, which is typically used for highly stressed machine parts. The advantage of this steel is low susceptibility to temper brittleness. Hardening is done in shallow quenching environment, because of the possibility of quenching cracks in places with notch effect or surface defects occurrence. In the hardened state they show good resistance to adhesive and abrasive wear. Chemical composition of steel 42CrMoS4 is shown in Table 1. Material properties of steel 42CrMo4 in quenched condition are shown in Table 2.

Table 1

Chemical composition of steel 42CrMoS4

Chemical composition [weight %]						
C	Cr	Mn	Mo	Si	S	P
0.38	0.9	0.6	0.15	Max	0,02	Max
0.45	1.2	0.9	0.3	0.4	0.04	0.025

Table 2

Mechanical properties of steel 42CrMo4 in quenched condition

Physical quantity	**Value**
Dimension	$16 < d \le 40$ mm
Yield point	$Re \ge 750$ Mpa
Tensile strength	Rm = 1 000 – 1 200 Mpa
Elongation	$A \ge 11$ %
Contraction	$Z \ge 45$ %
Impact energy	$KV \ge 35$ J

3.2. Metallographic analysis

Based on the nature of the shaft defect identified by the crack detection, attention was paid to the starting material of the shaft. We used six semi-finished products from which cross sections were cut for the evaluation of microcleanliness after cutting from bar stock [7]. On their surface macroscopical discontinuities were identified in one case, Fig. 3, which were marked for metallographic analysis sampling.

Microcleanliness rating revealed the presence of non-metallic inclusions in the central region and below the surface. From the macroscopically observed imperfections (scratches, cracks) of the shaft, see Fig. 3, cross sections were cut off to specify the kind of internal damage in detail. Occurrence of cracks was identified on the cross-section of a metallographic pattern; they were accompanied by oxidic phases, Figs. 4 and 5. The length of the crack was 0.135 mm and its depth 0.12 mm. Also a micro-overlap of depth 0.026 mm was identified below the surface.

When evaluating the cross section in the central region, lumps of contaminants with a cavity, Fig. 6, of size of 0.33 mm were identified [3]. Based on these findings, a scratch pattern of the longitudinal section was prepared,

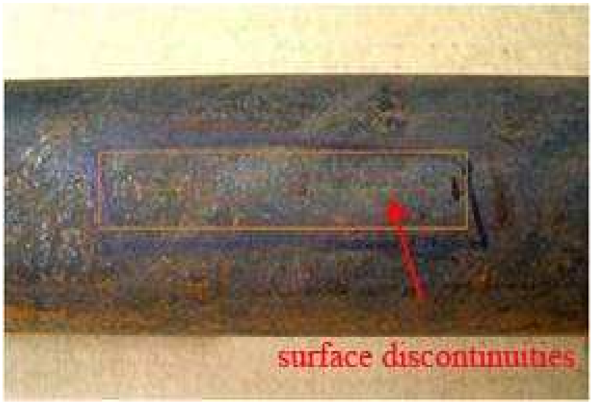
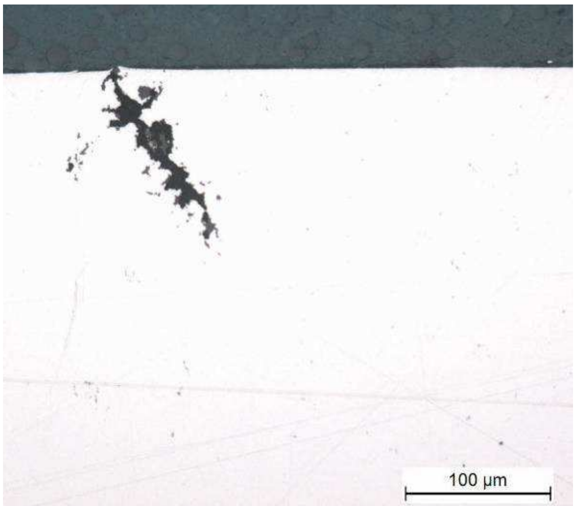
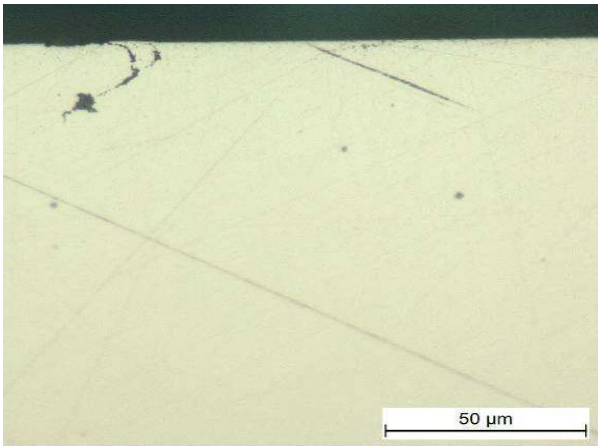


Fig. 3. Starting material – surface discontinuities.



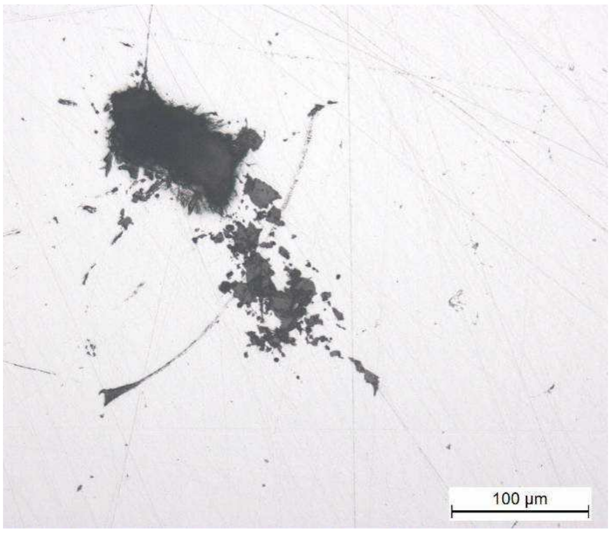
200× magnified

Fig. 4. Microcracks and micro-overlaps below the surface of the damaged material of the shaft – crack on the shaft surface.



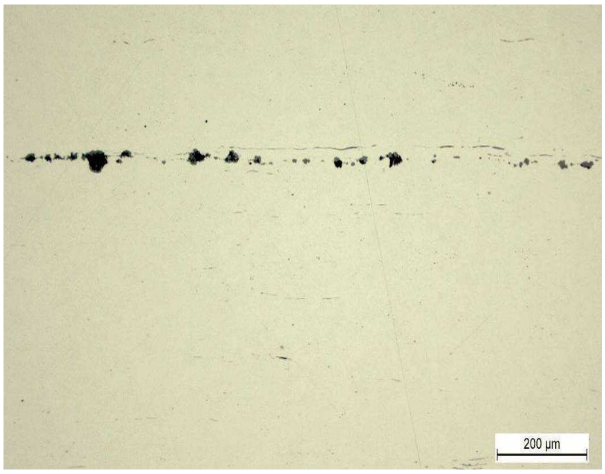
500× magnified

Fig. 5. Microcracks and micro-overlaps below the surface of the damaged material of the shaft – micro-overlap around the circumference of the shaft cross section.



200× magnified

Fig. 6. Cross-section of surface defects of the damaged shaft.

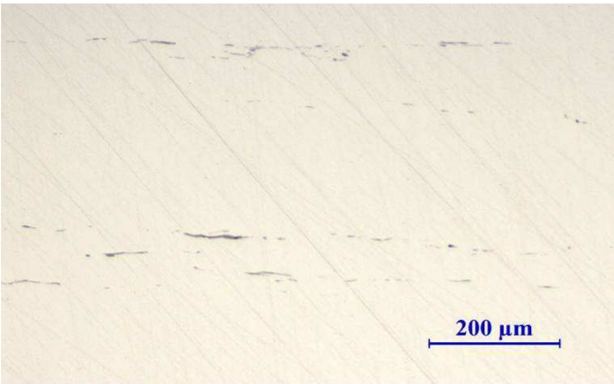


100× magnified

Fig. 7. Macro-inclusions in the body of the damaged shaft – longitudinal section.

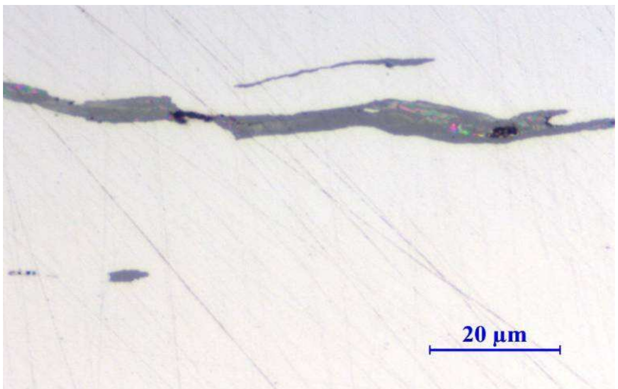
where the detail of oxidic macro-inclusions, of the length of 12.5 mm, was recognized, Fig. 7, according to the HMS 142 standard (according to DIN 50 602). The detail of sulphides occurrence micro-cleanliness corresponds to level 3, Figs. 8 and 9, according to the STN EN 10 247 standard. The microstructure of the damaged shaft in the crack region is formed by high hardened martensite, or fine sorbitol and ε –carbide, which is documented in the etched and non-etched state of the cross-section in Fig. 10. In the crack region no decarburization of the basic material was observed.

Changes in the microstructure of the basic material were only in the directing of the initial microstructure, which remained after the material forming technology [5]. Figure 11 shows longitudinal sections of the microstructure on the edge and in the central region of the metallographic sample, see Figs. 11, a, b, c, and d for different magnifications. These structures indicate that the semi-finished product shows finer arrangement of microstructure particles in unconnected lines in the peripheral region below the surface [7]. More significant coherent arrangement with wider lines was observed in the central region. With higher 200× magnification, it can be seen that the arrangement of carbide particles is not so significant. It is a larger scatter and thus the directing is not so sharply defined. Such microstructure is still acceptable in terms of further processing of the semi-finished product to the finished product. Microstructure detail, see Fig 12.



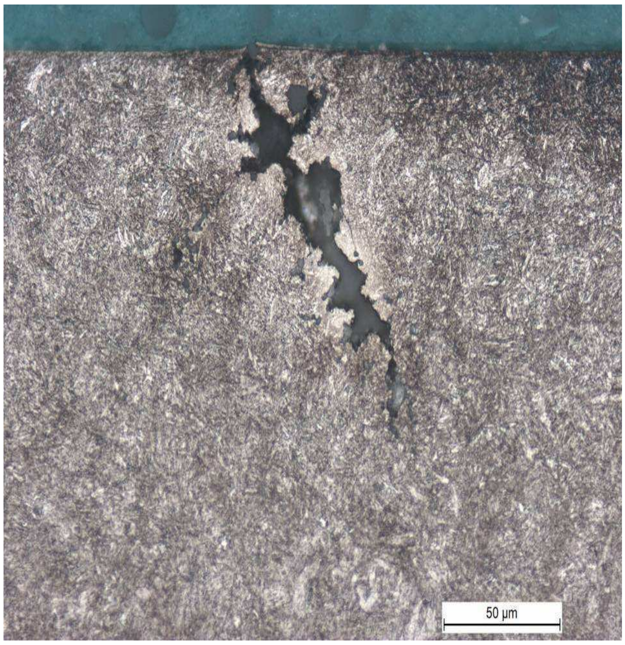
80× magnified

Fig. 8. Sulphidic phases in longitudinal section.



800× magnified

Fig. 9. Sulphidic phases in longitudinal section.



400× magnified

Fig. 10. Microstructure of the crack region of the damaged shaft.

a

b

c

d

Fig. 11. Microstructure of sample No. 2 longitudinal section: *a* – edge, 50× multiplied; *b* – centre, 50× multiplied; *c* – edge, 200× multiplied; *d* – centre, 200× multiplied.

Table 3

Hardness measure $HB_{5/750}$ along the length of the shaft

Hardness $HB_{5/750}$						
Measurements	1.	2.	3.	4.	5.	Average
$HB_{5/750}$	313	302	286	298	313	302.4 ± 11.3

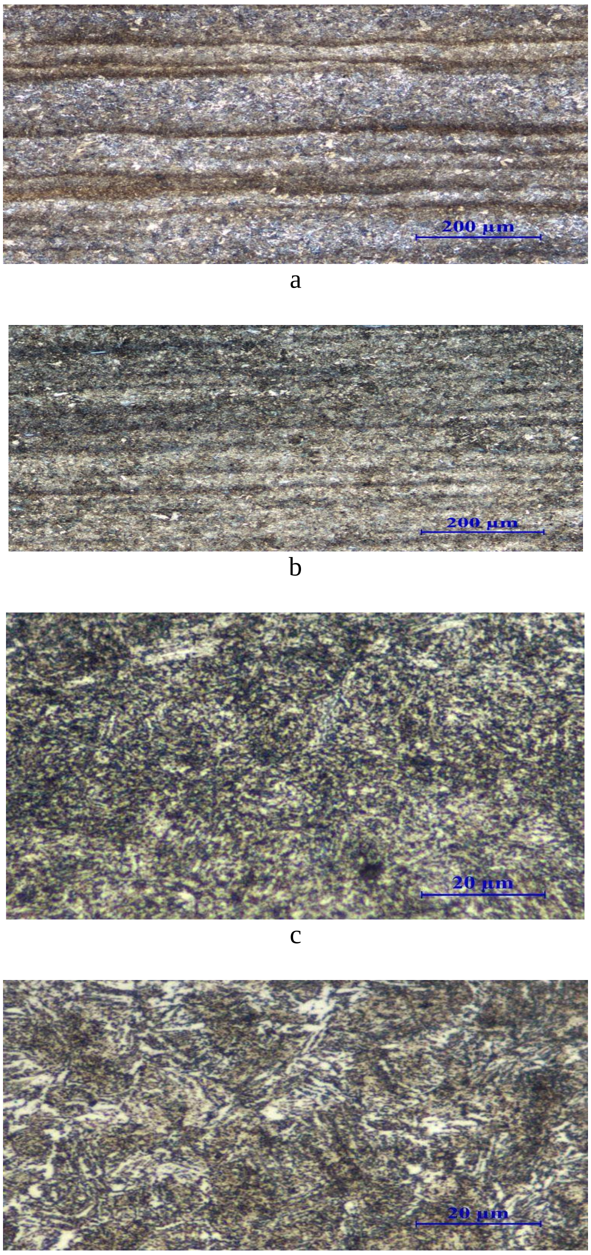


Fig. 12. Detail of longitudinal section microstructure of sample No. 2: *a* – sample centre 150x magnified; *b* – sample edge 150x magnified; *c* – sample edge 800x magnified; *d* – sample centre 800x magnified

3.3. Measuring of the hardness of the shaft

Measurement of the hardness of the basic material along the entire length of the shaft was carried out according to Brinell – $HB_{5/750}$, the measurement results are shown in Table 3, and individual measurement points are indicated in Fig. 2 (1–5). The average hardness with the measurement standard deviation is $HB_{5/750}$ = 302.4 ± 11.3. The HMS 142 standard requires the specified hardness $HB_{5/750}$ = 290–327 for shafts made of material 42CrMoS4.

4. CONCLUSIONS

The final product properties are largely influenced by the characteristic of surface and subsurface layers. For this reasons it is necessary surface properties devote considerable attention and prove in time to eliminate the causes leading to the development of these disorders. On the surface components, such as shafts and other rotating parts in the manufactoring process and machining technology, there are many influences that initiate the crack formation and development. Generally, we can divide the effects of external and internal influences and their combinations. The external influences include for example mechanical stress, chemical effects such as corrosion, physical effects such as technological processes (machining, heat treatment, forming), stray currents, radiation etc. Internal factors are formed by residual stress, surface morphology for example roughness, material and mechanical surface properties (structure and surface property, coating hardness stabilization, etc.) the presence of surface or subsurface defects and heterogeneous structure (inclusions, blow holes etc.) [7]. A comprehensive description of these effects is known as surface integrity [12–16].

The paper deals with the task of establishing the causes of the shaft damage which was identified in practice by the continuous intermediate inspection using the crack detection testing [8]. During the test of the shaft, spots with surface failure of the basic material were marked and macroscopically documented. The length of the identified cracks was h = 11.5 mm in the inspected spot. A more detailed analysis of the shaft microcleanliness showed a number of overlaps and cracks accompanied by contaminants in size h = 0.135 mm and h = 0.026 mm which occurred along the perimeter of the machined surfaces of the shaft. In the central region a cluster of contaminants with a cavity of size 0.33 mm was found and also directed macro-inclusions of length h = 12.5 mm were detected. Based on these facts, the inspection was completed with an analysis of the chemical composition of the damaged shaft, which, however, did not confirm the change in chemical composition and the content of individual elements in comparison with the required values. The chemical composition conforms to the material and the product [7]. The above evaluation of the microstructure indicates that at the edge of the shaft the linearity was finer and less continuous in comparison with the central region where the linearity produces directed wider zones. The microstructure of the assessed shaft and the semi-finished product is of martensitic - bainitic character, it is over-tempered (fine sorbitol) with the occurrence of ε – carbide [9]. It can be concluded that the cause of the failure of the region under the shaft surface is caused by a massive occurrence of macro-inclusions in the initial semi-finished product from which the shaft was made. According to the HMS 142 standard the microcleanliness of the material shall not exceed the value of K3 ≤ 40 and individual inclusions shall not exceed the level 5 according to DIN 50 602. The limit size of inclusions – level 5 has been exceeded, and macro-inclusions were observed, which became the main cause of the shaft damage during the final processing [9–11]. The microstructure quality (fine sorbitol) and material hardness of the evaluated shaft and the semi-finished products complied with the specified requirements.

This article gives a specific example of addressing the integrity of the shaft surface. The issue of a comprehensive solution is quite complex, because the authors only show the possible solution directions and developments in the field of surface integrity with possible errors in the evaluation [18–19]. The results of tests and analyzes must be evaluated not only *i* terms of the resulting values, but also in terms of subsequent links and contribution to a comprehensive understanding of the product.

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