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EVALUATION OF RESISTANCE TO CATASTROPHIC FAILURES OF LARGE-SIZE CATERPILLAR CHAIN LINKS OF OPEN-PIT MINING MACHINERY

OCENA ODPORNOŚCI NA USZKODZENIA KATASTROFICZNE WIELKOGABARYTOWYCH OGNIW GĄSIENICOWYCH PODWOZI MASZYN PODSTAWOWYCH GÓRNICTWA ODKRYWKOWEGO*

Large-size caterpillar undercarriages of basic mining machines are operated in extremely harsh conditions: they are subjected to high workloads and aggressive environmental influence. Under these conditions, the degradation can develop intensively and results in wear and tear of parts and subassemblies of these undercarriages. Especially dangerous are the catastrophic failures of components of the caterpillar chain: links or connecting pins (plastic deformations or brittle fractures), which generally exclude further work of the undercarriage. Because of that, a study on the structure of the damaged parts was carried out. Basing on numerical models of typical large–size chain links an assessment of effort of these parts was done, critical areas in their build were localized and proposals of modifications of their geometrical parameters were formulated as well. The main result of implementation of these modifications is a significant increase in links' resistance to catastrophic failure, which is particularly important in terms of operational safety and reliability of basic machines.

Keywords: *Large-size caterpillar undercarriages, degradation, failures of chain links, numerical strength analyses.*

Wielkogabarytowe podwozia gąsienicowe maszyn podstawowych górnictwa odkrywkowego pracują w wyjątkowo trudnych warunkach eksploatacyjnych: są poddawane ekstremalnie dużym obciążeniom roboczym oraz agresywnemu oddziaływaniu środowiska. W takich warunkach procesy degradacji mogą rozwijać się szczególnie intensywnie, a ich efektem są zużycie lub uszkodzenia elementów i podzespołów tych podwozi. Szczególnie groźne są uszkodzenia katastroficzne elementów łańcucha gąsienicy: ogniw lub sworzni łączących (odkształcenia plastyczne lub kruche pęknięcia), które wykluczają na ogół dalszą eksploatację podwozia. Mając to na uwadze, przeprowadzono studium struktury uszkodzeń elementów wielkogabarytowych podwozi gąsienicowych. Na podstawie modeli numerycznych dokonano oceny wytężenia typowych wielkogabarytowych ogniw gąsienicowych, wyznaczono obszary krytyczne i zaproponowano modyfikacje ich cech geometrycznych. Wynikiem tych modyfikacji jest znaczące zwiększenie odporności ogniw na uszkodzenia katastroficzne, co jest szczególnie istotne w aspekcie bezpieczeństwa eksploatacji maszyn podstawowych.

Słowa kluczowe: *wielkogabarytowe podwozia gąsienicowe, degradacja, uszkodzenia ogniw gąsienicowych, numeryczne analizy wytrzymałościowe.*

1. Introduction

Large-size caterpillar undercarriages of basic mining machines are subjected to extremely high workloads and are exposed to harsh environmental influence (low temperature, rain, dust, mud). In such circumstances, parts and subassemblies of these undercarriages are particularly vulnerable to degradation and damage.

Decisive impact on the scale and intensity of degradation processes of parts of the caterpillar undercarriages have values and character of the acting workloads. In this aspect, particularly dangerous are extremely high loads, unforeseen by the designer. They can result in sudden/catastrophic damages, associated with the destruction of entire elements – such as a plastic deformation and a brittle fracture.

Statistics show that damages of caterpillar chains account for about 15% of all cases of damages of the driving units of multi–bucket excavators (Fig. 2) [12]. Nearly 70% of them arise from operational reasons: due to high dynamic loads (especially during start-up and turning), severe tribological conditions in the chain (limited ability to provide adequate lubrication, which results in faster abrasive wear of the elements) and an aggressive influence of the soil environment (corrosion and aging of materials). Less than 10% of the total damages of the undercarriages' components in basic machines is caused by technological reasons – in particular imperfections of the materials or inadequate chemical-heat treatment.

2. Basic forms of degradation of chain links

The results of the degradation of large–size caterpillar undercarriages are the partial or total failures of their components, wherein approximately 80% of all cases comprise the partial ones, with a further work of the basic machine possible, although to a limited extent (e.g. at reduced speed and movement resistance).

In the context of the possible consequences of the caterpillar chain's damages, its links and connecting pins are particularly important. Almost every failure of one of the links or connecting pins excludes further work of the machine.

The research shows that the degradation of chain links occurs primarily in the following areas (Fig. 3) [12]:

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

Fig. 1. Basic subassemblies of a large-size tracked undercarriage: A – caterpillar chain, B – supporting wheels, C – balance lever's units, D – driving wheel, E – caterpillar's girder [authors' archive]

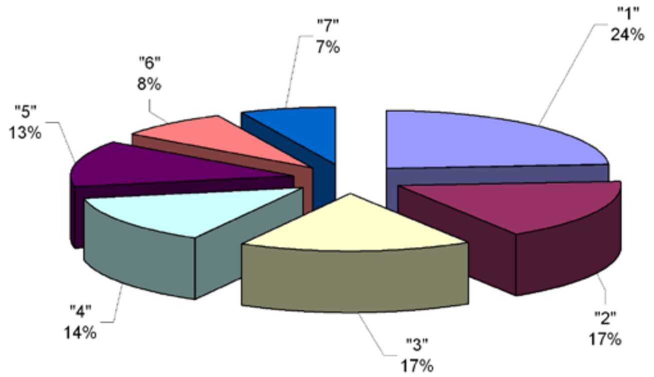

Fig. 2. The structure of failures of caterpillar undercarriages of basic machines in Polish open-pit mines: 1 – unit of upper supporting wheel, 2 – unit of balance lever and carriage, 3 – girder's supporting structure, 4 – caterpillar chain, 5 – unit of driving wheel, 6 – unit of turning wheel, 7 – drive of the caterpillar [12]

- In the area of lugs (zone „1", Figure 3). The degradation in these areas is an effect of extremely high workloads, unexpected in the normal operation. Such situations may occur for example during a turning process with a curve radius too small, especially in case of turning in place. It can result in a plastic deformation or a fracture of lugs and each of these cases is virtually irreparable damage, rated as a so-called catastrophic one.
- At the surfaces of holes in the pin joints in the links' lugs (zone "2", Figure 3). This degradation is an abrasive one and is caused by friction between the pins and bushings with corrosion and mechanical impurities inside the joints.
- At the surface of the raceway of the links (zone "3", Figure 3). This degradation is an effect of rolling out of the upper part of the link by rolling wheels. In addition, impact loading may appear when rolling wheels overrun subsequent links.
- At the front and rear of the upper parts of the links in the contact area with driving wheel (zone "4", Figure 3). The degradation of these areas is a result of the impact of driving system's teeth. Due to the necessity of the combine forward or backward movement, the degradation occurs in both the front and the rear zone of the link.
- At the base of the link's lugs (zone "5", Figure 3). Degradation in this area is caused by friction between subsoil and links under the action of large loads (unit pressure of 100 kPa).

Degradation of pins connecting links is relatively easy to remove by replacing the pin with a new or a remanufactured one. A little more cumbersome is to remove effects of the degradation of the holes in the pin joints. In such cases, the repair consists in replacing the bushing. Degradation of the lugs in the chain links: a plastic deformation and a brittle fracture (Fig. 4), evolving under the influence of overload is usually an irreparable damage and qualifies the entire link to be replaced. Often in such cases it is also necessary to exchange the two mating

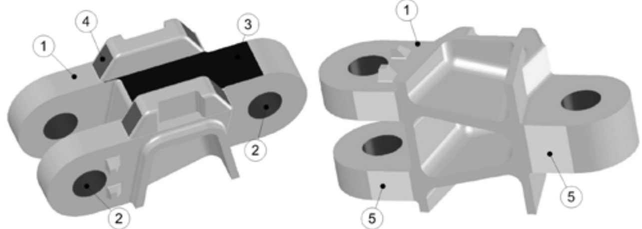

Fig. 3. Areas of basic degradation of large-size chain links [12] (detailed description in the text)

links. This entails significant costs resulting not only from the cost of the links, but also including losses generated from the out–of–order state of the machine.

Small plastic deformation of links' lugs does not always mean a need for instant exchange of the link, but continued usage of such a part could result in damage to other parts of the driving unit.

A typical example of the negative consequences of continued use of links and connecting pins with plastic deformations is a phenomenon called bevelling of crawler treads which causes an uneven distribution of loading on the subsoil. In extreme cases, this can lead to damage to the crawler treads by their mutual overlap.

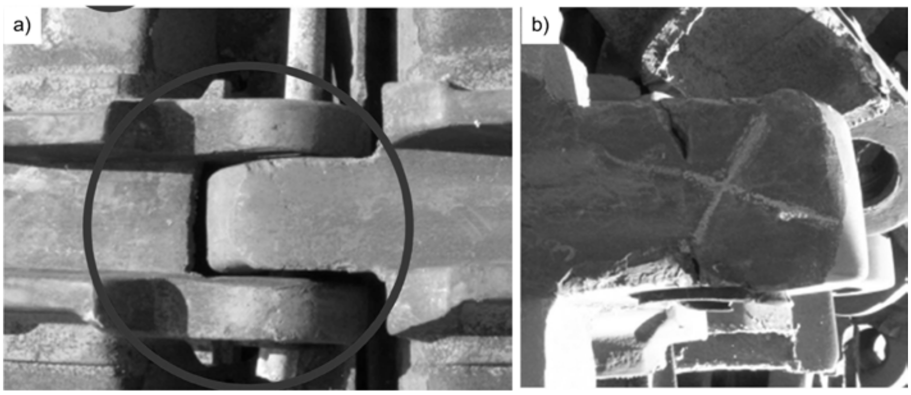

Fig.4. Examples of failures of links' lugs: a) plastic deformation, b) brittle fracture [authors' archive]

A degradation of a pin joint hole which is made directly in a link's lug (e.g. ovalisation or fissure of surface) is an irreparable damage, which qualifies the whole link to be replaced. One way to enable repair of the damaged pin joint's holes is to use a bushing which, after reaching the wear limit is exchanged for a new one – without the need for replacing the entire link.

The main causes of a gradual degradation of the pin joint holes are unfavourable tribological conditions (high values of unit loading make it difficult to obtain proper lubrication while hard inclusions act as an abrasive) and corrosion (water and mud causing an accelerated destruction of the holes' and pins' surfaces due to an aggressive chemical influence).

3. Short review of state of the art in operational issues of chain links

There are plenty of scientific achievements related to the subject of operation of large-size caterpillar undercarriages of basic mining machinery.

An extensive study on the general problems of long-term degradation of multi–bucket excavators and stackers is given in [5, 7]. A unique position in the literature describing in details the effects of the degradation of basic mining machines in Polish coal mines is a work [1].

Publications relating to specific issues in the field of degradation of caterpillar undercarriages' components are focused on the following main thematic groups:

- identification of workloads,
- issues of strength,
- analysis of the degradation processes,
- designing issues,
- operational issues.

The problem of determining workloads acting on parts of large–size caterpillar undercarriages was analyzed among others in [9, 10]. An empirical method for evaluation of traction forces during the operation of basic mining machinery was presented.

A case of a damage of a driving shaft of an undercarriage of a multi–bucket excavator is the subject of work [8]. Based on a numerical analysis and measurement's results it was showed that the main cause of the failure was the wrong shape of the shaft's end, which led to the formation of the constructional notch in this area. As a result the shaft was twisted through the development of local plastic deformations and stresses surpassed the fatigue strength [8].

The issue of the strength of caterpillar undercarriages' components is presented, inter alia, in works [3, 11, 13]. The case of the degradation of stackers' chain links is analyzed in detail in [3]. It was showed that the main causes of the damage were material defects: microcracks and precipitation of carbides. In [2] damages of elements of a bucket wheel excavator's undercarriage were analyzed: balance levers, links and crawler treads. Basing on numerical simulations it was shown that the cause of the damages was too low strength of these elements on a lateral loading.

Issues related to a rational design of caterpillar chains' parts: links, connecting pins and treads are objects of interest especially by designing centres. In this regard, a particular achievement is a novel solution of friction node "bushing – pin" connecting links. It was developed by the Designing-Technical Office SKW [14]. This node is protected against the rock-soil particles getting inside.

Publications in the field of operational issues of large-size caterpillar undercarriages include issues of new materials, lubricants and lubrication techniques that could be used in nodes connecting links. The usage of conventional lubricants in heavily loaded nodes does not always enables to obtain better tribological characteristics.

Original solutions in this area were developed at the Division of Fundamentals of Machinery Design and Tribology in the Wroclaw University of Technology. One of these solutions is the application of lithium grease mixed with PTFE powder, which significantly increases the efficiency of lubrication, while lowering wear of the friction elements [6]. Another proposal is to use grease with the addition of graphite and molybdenum disulfide in the form of powders, which significantly reduces the shear stress in the lubricant and thus lowers the resistance to motion in the lubricated node [4]. Both of these solutions can be used in caterpillar chains of undercarriages in large-size mining machines.

4. Strength analysis – limiting loading of chain links

Pin joint hole is a notch in the chain links' lugs sections. Therefore, it is one of the most vulnerable areas to damage in the structure of the links, particularly under conditions of high lateral forces. In extreme conditions, regardless of the links' damage, it may inter alia effect in broken drawbar which steers the process of turning of the entire machine. Such a case is described in detail in [1].

In view of the possible consequences of lugs' damage, the authors have developed basic numerical models of large-size links used in excavators' and stacker's undercarriages. One such a model of links type "I" is shown in Figure 5.

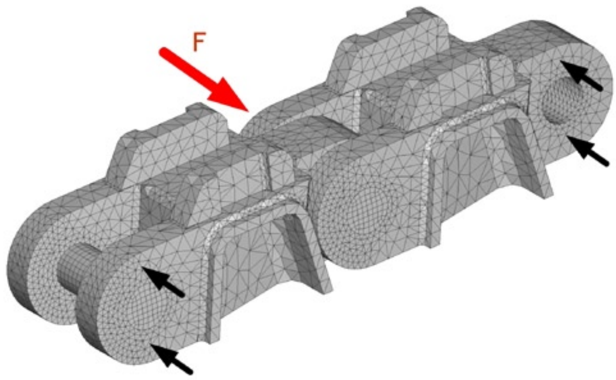

Fig. 5. Discrete model of "link – pin – link" connection [12]

Strength analyses were carried out using finite elements method for lateral loads in the range of F = 10÷10,000 kN, assuming some specific boundary conditions (support of links' connection). In the calculations the strength and ductile properties of cast steel L35GSM (Yield strength R_e = 850 MPa among others) as the material from which the links are made were taken into account. As the main objectives of the numerical simulations the following were assumed:

- To determine critical areas of the links' structure particularly vulnerable to the formation of defects because of a concentration of stresses.
- To estimate the value of the limit load, causing the destruction of the links, such as a plastic deformation and a brittle fracture.

Basing on results of the calculations it was found out that one of the most dangerous areas in the "link – pin – link" connection zone are bases of the narrow lugs. It was also shown that the limit value of lateral load which surpassing results in plasticizing of the links type "I" is about $F_{max} \approx 3000$ kN. Exemplary results of stress analysis for such values of load are shown in Figure 6.

The results of these calculations were verified with the research realised in the Division of Reliability Engineering and Diagnostics from Institute of Machinery Design and Operation at Wroclaw University of Technology. The test were carried out at a laboratory of a manufacturer of these links.

On the basis of the standard PN-G-47000-2: 2005: "Open pit mining. Multi-bucket excavators and stackers. Part 2: Introduction to computing" it was assumed that the required safety factor of links related to the yield stress is X = 1,3. This means that the maximum value of the stress in the links, as defined by Huber – von Mises yield criterion should not exceed 650 MPa.

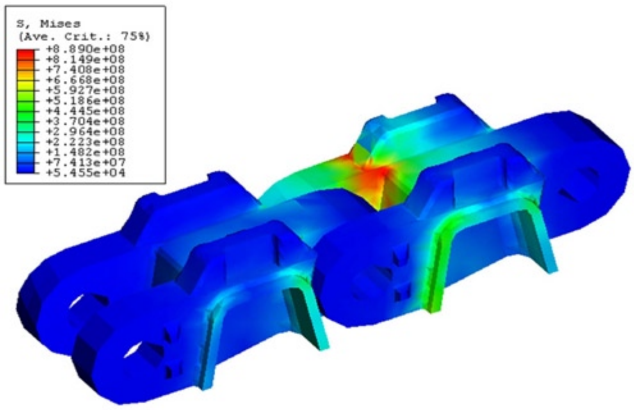

Fig. 6. Exemplary distribution of von Mises stress in the "link – pin – link" connection under the influence of plasticizing lateral loading.

With this in mind, concepts of geometrical modification of the links in their critical areas were developed. It is where the material's plasticization occurred. In particular, changes were introduced in the areas of bases of both the narrow and the broad lugs. Modifications included as well surfaces of the links mating with the driving wheel. These modifications are described in detail in [12]. The results of the simulation of effort of links with modified geometry are shown in Figure 7.

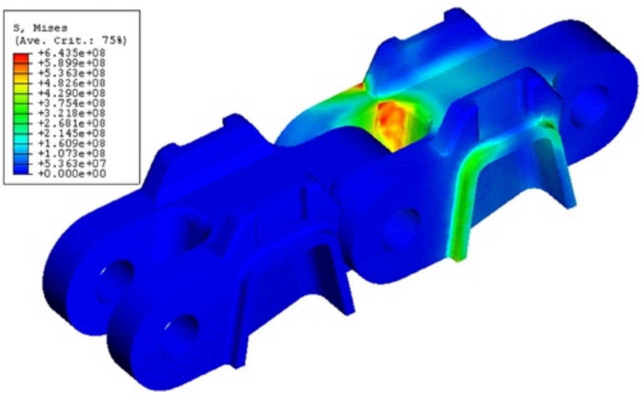

Fig. 7. Exemplary distribution of von Mises stress in the "link – pin – link" connection under the influence of plasticizing lateral loading after applying modifications of the critical areas.

It is noticeable that after the changes in the geometry of the critical sections, as proposed by one of the authors [11, 12], a significant reduction in the maximum values of von Mises stress is achieved (up to the level of 650 MPa).

This also means that the modified chain links are able to carry the load capacity larger by about 30% when compared to currently used links. This can help to increase the safety and reliability of caterpillar undercarriages of basic machinery.

4. Summary

Chain links are among the key elements of undercarriages of large–size basic mining machinery. Their degradation occurs in most of cases, because of operational reasons i.e. due to high workload and adverse environmental conditions (dust, mud, low temperature).

In this context it is important to understand the mechanisms of degradation of these elements, as well as to identify the so-called critical areas which are particularly vulnerable to damage and as well to determine load limits resulting in damage of the links: either plastic deformation or brittle fracture.

With this in mind, basing on a statistical data analysis from repair divisions in Polish coal mines and the authors' own research the structure of typical forms of degradation occurring in large–size chain links was determined. Cases of both gradual degradation (wear, corrosion), and a sudden/catastrophic one (plastic deformation, chipping, cracking) were included.

In order to perform strength analysis geometrical models of typical chain links used in caterpillar undercarriages of basic mining machinery were made. Numerical simulations of effort of the links for different variants of lateral external loads were performed. On this basis, critical areas in the structure of the analyzed links particularly vulnerable to damages were designated and the ultimate values of loading that causes the damage were calculated.

In order to increase the resistance to failure of the chain links, concepts of changes of their geometrical features in critical areas were developed. The effects of these changes are: an increase of about 30% of the limit load and a reduce of the links' effort under current maximum level of workload.

The implementation of these modifications can help to improve the reliability of large–size caterpillar undercarriages, because operation of chain links even partially degraded can initiate the process of destruction of other undercarriage's components – as a kind of a "domino effect". A striking example of this is a damage of crawler treads due to bevelling.

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