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Numerical and experimental analysis of a mine's loader boom crack

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Analysis and modelling

ABSTRACT

Purpose: The main purposes of the paper are to discuss designing problems of machines used in underground mining and investigation of its reasons based on cracked boom of underground mine machine.
Design/methodology/approach: Numerical and experimental approach was considered. The finite element method was used for numerical simulation. Fractographic and microscopic evaluation, chemical analysis, hardness tests were used to perform material evaluations. The objectives are achieved by numerical simulation of cracked loader boom, material evaluations of specimens and comparison of results achieved from both approaches. These were determined through a numerical experiment, based on a discrete model of the jib boom and predefined boundary conditions. The finite element analysis for the jib boom provided information about stress distribution for extreme load conditions. The study included macroscopic and fractographic inspection, microscopic evaluation as well as hardness tests of the material used for the jib boom. Conclusions from both approaches were drawn then.
Findings: The causes of damage of a loader jib boom used at an underground copper mine were found.
Practical implications: The study provides practical implication into designing process of mentioned objects by wider view of relationships between theoretical design and manufacturing process.
Originality/value: The paper provides information backed by evaluation and test results, stating the nexus of causes of the boom failure. The experimental and numerical approaches show relationship between designing and manufacturing process of machines. This can be helpful for the designers and researchers looking for reasons, methods of investigations or how to prevent failures of similar machines.
Keywords: CAD/CAM; Materials; Metallography

1. Introduction

Machines used in underground mining, such as: derricks, roof bolting machines, loaders, transportation vehicles as well as others are generally used for ore exploitation, loading and transportation, i.e. basic mining tasks [1]. Construction design practice, exploitation and tests prove that such machines as well as their sub-components are subject to requirements radically different from machines operating on the surface. In general exploitations conditions are much heavier. Considering their specific application, they are subject to adverse operating conditions, variable operating conditions and are often subject to percussive loads (fig. 1).

Fig. 1. SWB (Self-propelled roof ripping vehicles) during operation at an underground mine

Design of mining machines requires from the constructor to use quick and accurate calculation methods. The design should

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result in a reliable construction, withstanding the required loads, whilst also being economical [2]. This can be achieved through the use of modern integrated CAD/FEM systems. Other approaches can be also used for the designing purpose and in order to achieve loads coming from operational conditions [3, 4].

Even though modern design methods are already employed, we still observe damage of load bearing elements of machines. Some of the reasons for this include:

- design errors – lack of precise calculation methods (older construction), load underestimate, simple mistakes made by designer, neglecting influence of some factors such as residual stresses, mean stress, fits influence [5], which in certain circumstances can drastically change stress effort of structures. This situation is observed in welded structures, forged and cast parts,
- technological errors – during the design or production stage: incorrect technology, wrong fits in connection, bad welds quality and wrong welding technology, material faults – incorrect steel grade, lamination of material in tensioned connections,
- exploitation errors – overloads caused by improper exploitation or by unpredicted circumstances, exploitation with mechanical failures.

A precise analysis of damage occurring during exploitation allows for better understanding of circumstances and causes of faults, thus allowing for improvement of design of future objects.

Among the vast number of machines operating in underground mines, we would like to concentrate on loaders. A common fault, which is found in machines of this type is damage to the scoop bucket and the cutting blade. There are also cases related to damage of the frame or the loading jib. During exploitation of one of such machines in an underground copper mine, the jib suffered damage as shown in fig. 2. This consisted of a cross fracture of the jib boom, causing complete separation of the front part of the jib from the rest of the machine. The fault occurred during unloading of the scoop.

Fig. 2. Damaged loader boom

In order to determine the causes of the jib damage, a decision was made to verify the design of the machine, using CAD/FEM numerical stress assessment of the jib boom. Furthermore, detailed material analysis was also performed, to check for possible material and technological faults, which could also be plausible causes of this damage.

2. Numerical experiment

The geometrical model of the jib boom was used to create a discrete model. Digitization was performed using the finite element method [6, 7 and 8] assuming:

- modeling of sheet metal using ‘Shell’ elements,
- modeling of connectors, actuators, axles and bolts / pins using modified ‘Beam’ elements,
- modeling of bearing nodes using ‘RBE3’ type elements,
- modeling of the scoop bucket and the boom using ‘Rigid’ type elements.

The digital model of the jib boom is shown in fig. 3.

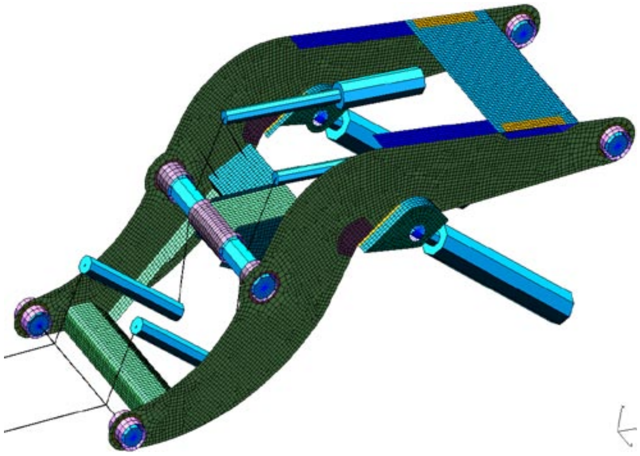

Fig. 3. Discrete model of the jib arm

According to technical parameters of the loader the analysis assumed four positions of the jib boom. One of assumed position is shown in fig. 4. Stress analysis was performed for 18 different cases. Each of these assumed a fixed position of the scoop bucket, with the stress load being generated by the actuators. A simplifications was made, assuming the scoop bucket as an ideally rigid construction, similarly a same assumption was made for its rotation axis [9].

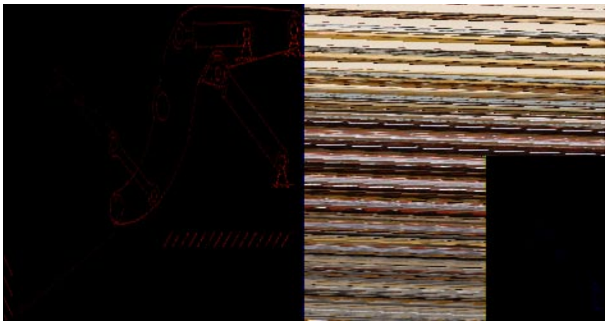

Fig. 4. Diagram of jib boom positions and loads

The stress calculations for the jib boom were performed using finite element analysis using the I-DEAS [10] system. Sample stress calculations are presented in fig. 5.

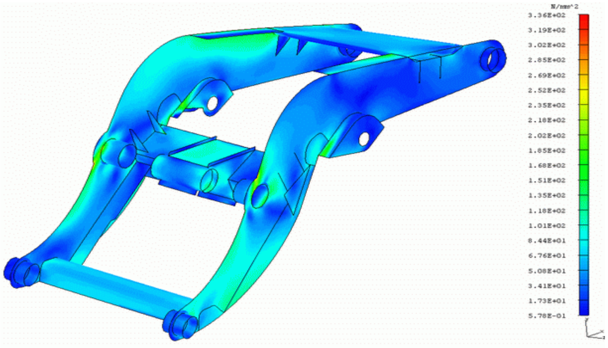

Fig. 5. Contour lines representing stress levels in the boom, according to the Huber-Mises theory

The computations provided a 3D representation of the stress levels as well as show the deflection of the jib boom, depending on the load size and geometrical configuration. The most representative case was determined. The maximum combined stresses in this case are:

$$\sigma_{MAX} = 413 \text{ MPa}$$

Stress concentration is caused at a structural notch at the boom's actuator mounting point. At this point there is also a change in the rigidity of the boom's side strip caused by the bushing for the actuator mechanism's mounting bolt. This is also the point where the boom cracking was initiated.

3. Material evaluation

The damaged jib boom as well the materials it is made of were evaluated using the following methods [11]:

- macroscopic visual inspection as well as stereomicroscope inspection using magnifications up to 30x,
- fractographic evaluation - scanning electron microscope,
- chemical analysis,
- microscopic evaluation,
- hardness tests.

3.1. Macroscopic and fractographic evaluation

The boom supplied for testing had a fracture running across the entire cross section of the boom (fig. 6).

The fractographic analysis concluded that the fracture was an immediate brittle fracture, originating at points marked A and B in fig. 6, located along the S1 weld joint fusion with the boom material. Analyzing the surface topography of the fracture points A and B using a scanning electron microscope showed a smoothed surface, which is characteristic for fracture origination points. The fractures at points A and B probably originated already during or shortly after welding, and ultimately lead to an immediate brittle fracture of the jib boom. It is also probable that the welding fractures lead to a small fatigue zone. Surface morphology observed at point A is shown in fig. 7.

Macroscopic evaluation of the weld joint was performed at the cross microsection of the S2 fillet weld (fig. 8). The weld surface was etched using Adler's etching solution (Ma11Fe).

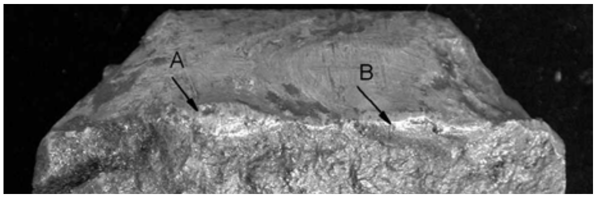

Fig. 6. Topography of the fracture zone

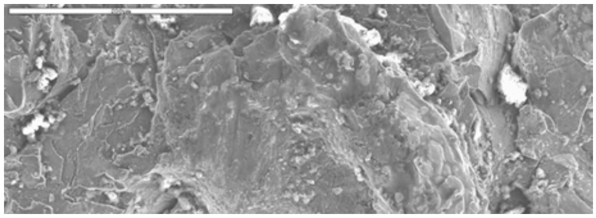

Fig.7. Surface morphology at point A - fig.6. SEM image

Observations proved incomplete weld penetration at the root of the fillet weld. Both welds as well as the weld fusion line also exhibited numerous welding errors in the form of interruptions as well as gas bubbles. The macrostructure examination of the weld joint also revealed various structures in the flat bar, jib boom and weld joint materials as well as within the HAZ (heat affected zone).

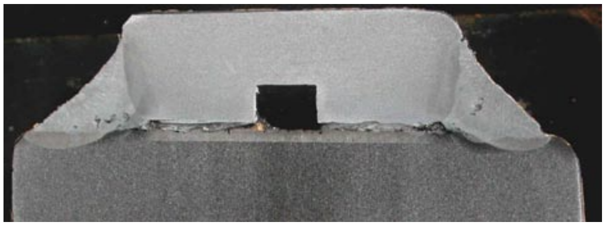

Fig. 8. Weld joint between the flat bar and jib boom

3.2. Microscopic evaluation

Microscopic evaluation was performed for the cross microsection of the weld joint, which was earlier subject of the macroscopic evaluation.

After etching with Mi1Fe it was concluded that the jib boom material microstructure outside of the weld joint is a ferritic-perlite structure exhibiting slight characteristics of a Widmannstätten structure (fig. 9). This type of structure results in weakening of the mechanical parameters and also causes problems during welding, because of the non-homogeneous chemical composition of the material. The weld area has a perlite (pseudoeutectoid) structure with local occurrences of bainite. The pseudoeutectoid structure of the joint suggests that welding was performed using a medium carbon welding rod.

The heat-affected zone exhibits small plate perlite structures as well as areas of martensite structure, where the HAZ was hardened, thus leading to formation of brittle cracks. When comparing the jib boom material and the HAZ there is a clear difference between the ferritic-perlite structure of the jib boom and the perlite structure of the HAZ and weld joint. This rapid change of structure leads to significant change of parameters at the connection of the welded material and weld joint. It suggests also, that the weld was performed using an improper welding rod, having a significantly different composition as compared to the welded materials. The microstructure of the weld joint, HAZ and the welding errors are shown in fig. 10.

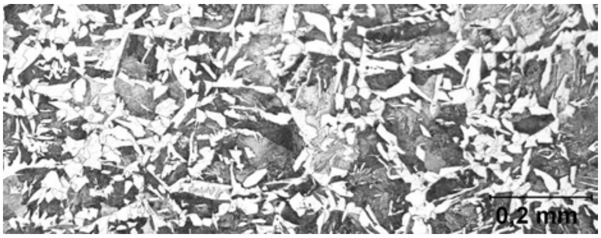

Fig. 9. Microstructure of the jib boom material

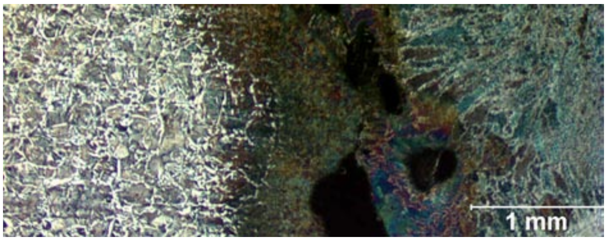

Fig. 10. Microstructure of the weld - HAZ and weld joint

3.3. Hardness testing

Hardness was checked using the Vickers method, using single impressions according to the Polish standard PN-EN 1043-1. The tests showed significant hardening of the HAZ at the weld joint with the jib boom material with local hardening of the material, which lead to occurrence of the brittle fractures.

4. Conclusions

The main purposes of the paper were to discuss designing problems of machines used in underground mining and investigation of its reasons based on cracked boom of mining machine, which suffered damage as shown in fig. 2. Numerical and experimental approaches were used in order to achieve wider point of view of such accidents, which happens in this type of machines.

Based on the performed boom material tests, evaluation of the fracture, weld joint between the flat bar with the lubrication groove and the jib boom side strip as well as the MES stress analysis, it was found that:

1. The microscopic evaluation of fragments etched using Mi1Fe, proved that the material of the jib boom outside of the weld has a ferritic-perlite structure showing slight evidence of Widmannstätten structure characteristics. This structure resulted from improper heat treatment and forging, meaning that the metal used for the jib boom was insufficiently rolled and thus has lower mechanical strength. It also makes welding of this material difficult.
2. Calculation of the carbon equivalent according to the Polish standard PN-86/H-84018, based on the chemical composition of this steel determined during testing, is 0,453 % and is close to the allowable value of 0,46 %. However, the evaluated jib boom steel has poor weldability, which should be taken into account before performing any welding repairs;
$$CE = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15 = 0{,}22 + 1{,}40/6 = 0{,}453\ \% \leq 0{,}46\ \%$$
3. The finite element analysis performed for a wide variety of loads proved that the brittle fracture occurred at a structural notch, causing concentration of stress forces. The maximum combined stresses in cases where the jib boom was subjected to torsion forces amounted to: $\sigma_{MAX} = 336 \div 413$ MPa.
4. It was concluded that welding performed without information (which could only have been obtain through laboratory material analysis) about:
   - presence of Widmannstätten structures
   - borderline CE Carbon equivalent value
   - caused introduction of additional residual stress and local change in material characteristics (material hardening). This in turn accelerated the occurrence of brittle fracture.
5. The jib boom fracture was inevitable, because the material is defective and has an improper structure. The loader jib boom thus has limited fatigue life.

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