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# THE ANALYSIS OF THE WATER-EXPANDED ROCK BOLTS RUPTURES DURING PRESSURE TEST

# ANALIZA PĘKNIĘĆ ROZPRĘŻANYCH WODĄ KOTW GÓRNICZYCH W TRAKCIE PRÓB CIŚNIENIOWYCH

This paper describe the investigation of a water-expanded rock bolts failed during pressure test (inner water pressure of 330 bar). A main objective of this work was to determine the cracks nucleation and propagation mechanism. It was found that the rock bolts failure was promoted by presence of non-metallic inclusions (mainly long sulphide inclusions) but the primary cause of cracking is strain ageing of steel. Suggestions for improving the behaviour of steel used for water-expanded rock belts by the modification of its chemical composition are proposed finally.

**Keywords:** failure; water-expanded rock bolt; non-metallic inclusions; strain ageing

W pracy opisano badania rozprężanych wodą kotw górniczych, które uległy pękaniu podczas prób ciśnieniowych (przy ciśnieniu wody wewnątrz kotwy 330 bar). Głównym celem badań było określenie mechanizmu zarodkowania i propagacji pęknięć. Stwierdzono, że propagacji pęknięć sprzyjała obecność wtrąceń niemetalicznych (głównie długich wydzieleń siarczków) ale podstawowym powodem występowania pęknięć jest zjawisko starzenia po zgniocie. W celu zminimalizowania występowania pęknięć, w pracy zaproponowano modyfikację składu chemicznego stali na tego rodzaju kotwy górnicze.

**Słowa kluczowe:** pękanie; kotwy górnicze; wtrącenia niemetaliczne; starzenie po zgniocie

## 1. Introduction

The selection of correct type and quality as well as delivery conditions of steel used for equipment in mining industry is very important and ensure a longer service life and less downtime (Peterka et al., 2014; Furuly et al., 2014; Shukla et al., 2013; Krawczyk & Pawłowski, 2013;

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Pawłowski & Bała, 2012), however, as it was stated in (Dhillon, 2008), in the industrial sector reliability is frequently expressed in terms of mean time between failures.

Rock bolting provides strength to the rock mass through a combination of friction and mechanical interlock on the interface between the bolt and the rock strata (Gamboa et al., 2005). Bolts are used as permanent and temporary support systems in tunneling and mining operations (Chen, 2013). The water-expanded rock bolts are made of a steel welded tube folded on itself and sealed at one end. It is expanded using a high pressure (about 330 bar) water flow provided by a special pump. The bolt is expanded inside a borehole, and the installation process is simply and easy, as it is shown in Fig. 1 (*Swellex rock bolts...*, 2009).

The cross section of steel rock bolt befor and after installation is shown in Fig. 2.

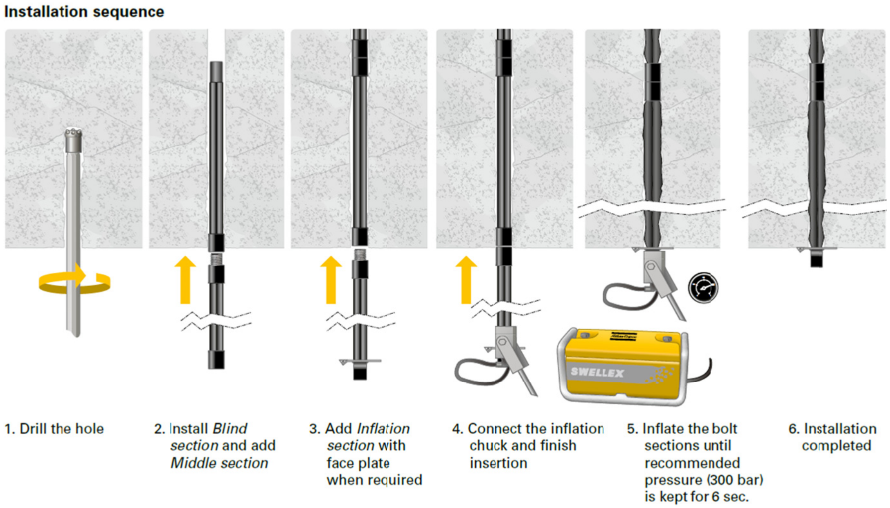

Fig. 1. The six steps of Swellex rock bolts installation (*Swellex rock bolts...*, 2009)

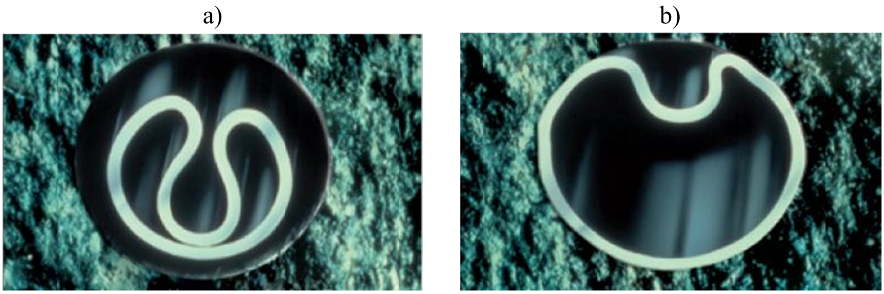
a) b)

Fig. 2. The Swellex steel rock bolt: a) before and b) after installation (*Swellex rock bolts...*, 2009)

This paper describe the investigation of a series of the water-expanded rock bolts, made of various S355MC steel melts, failed during pressure test (inner water pressure of 330 bar). Conducting such pressure test by the manufacturer is required by the customer and is mandatory for each delivery. The pressure tests were performed on the manufacturer special laboratory stand (without bore hole, just using a high pressure – 330 bar – water flow). A macroscopic view of examinated bolts is presented in Fig. 3, including bolt not checked by the pressure test). The bolt samples were prepared by the manufacturer as representative for the observed three failure types.

As it can be seen in Figure 3, samples after pressure test have longitudinal cracks, through-wall crack for the sample no 1, lower depth of crack for sample no 2 and a continuous band of small inner surface cracks for sample no 3 (an enlarged image of this area is shown in Fig. 4).

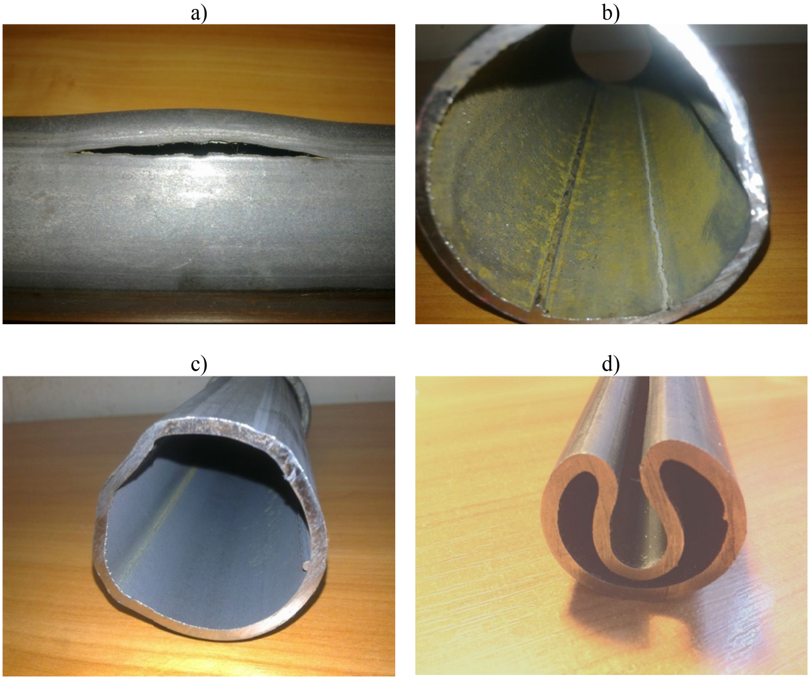

Fig. 3. A macroscopic view of the examined 36,5×34×3 mm bolts: a) sample no 1 – throughout crack, b) sample no 2 – crack depth approximately 0,2 mm, c) sample no 3 – microcracks depth no more than a few micrometers level, d) sample no 4 (not checked by the pressure test)

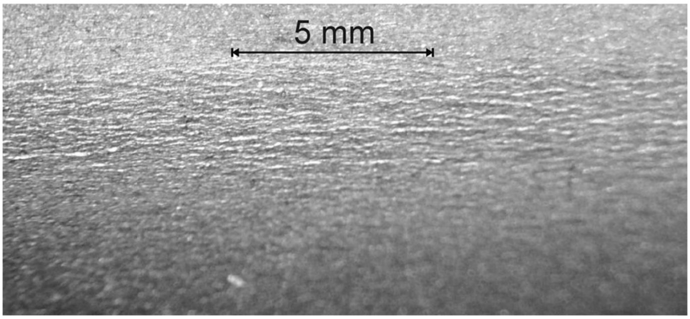

Fig. 4. A continuous band of small cracks on the inner surface of the bolt, sample no 3

## 2. Experimental procedure

The chemical composition of the samples was examined by mass spectrometer Foundry Master WAS. Hardness measurements, by Vickers method according to ASTM E92 standard, were made using the load of 294 N to determine cross-section hardness distribution of the investigated samples. Characterization of microstructures was performed by an Zeiss Axiovert 200MAT light microscope and Hitachi SU-70 scanning electron microscope equipped with an Energy Dispersive X-ray Spectrometer (EDS), which provides chemical analysis in the field of view.

## 3. Results and discussion

The chemical composition of the tested samples (bolts after pressure test) are presented in Table 1. As it is shown, chemical compositions meet the requirements of EN Standard for S355MC steel.

TABLE 1

The chemical composition of the tested samples of rock bolts, mass %

| Element | EN 10025 | Sample no 1 | Sample no 2 | Sample no 3 |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| C | max. 0,16 | 0.0779 | 0.0911 | 0.0788 |
| Si | max. 0,55 | 0.0087 | <0.005 | <0.005 |
| Mn | max. 1,70 | 0.711 | 0.512 | 0.545 |
| P | max. 0,035 | 0.0099 | 0.0046 | 0.0068 |
| S | max. 0,030 | 0.0068 | 0.0064 | 0.0041 |
| Cr | max. 0,035 | 0.0216 | 0.0163 | 0.0195 |
| Mo | max. 0,15 | <0.005 | <0.005 | <0.005 |
| Ni | max. 0,55 | <0.005 | <0.005 | <0.005 |
| Al | min. 0,015 | 0.0481 | 0.0403 | 0.0354 |
| Co | — | 0.0031 | 0.0028 | 0.0035 |
| Cu | maks. 0,60 | 0.0235 | 0.0193 | 0.0285 |
| Nb | maks. 0,06 | 0.0150 | 0.0202 | 0.0145 |
| Ti | maks. 0,06 | <0.002 | 0.0118 | 0.0077 |
| V | maks. 0,012 | <0.002 | <0.002 | <0.002 |
| W | — | <0.015 | <0.015 | <0.015 |
| Pb | — | <0.025 | <0.025 | <0.025 |
| Sn | — | <0.002 | <0.002 | 0.0039 |
| B | — | <0.001 | <0.001 | <0.001 |
| Ca | — | 0.0008 | 0.0004 | 0.0002 |
| Zr | — | <0.002 | <0.002 | <0.002 |
| As | — | 0.0111 | 0.0112 | 0.0067 |
| Bi | — | <0.03 | <0.03 | <0.03 |

However, it is worth mentioning that the sample no 1 (with a crack through the entire thickness of the wall) has the lowest total content (compared to other samples) of the so-called stabilizing elements (binding interstitial carbon and nitrogen atoms): niobium, vanadium and titanium, which eliminate or significantly reduces so-called strain ageing phenomenon, typical for this steel grades (Baird, 1971; Hosseini, 2015).

Hardness measurement revealed that for all investigated samples cracks are in the areas most strengthened due to plastic deformation during the forming of the rock bolt and the next expansion during pressure test as it is shown in Figure 5.

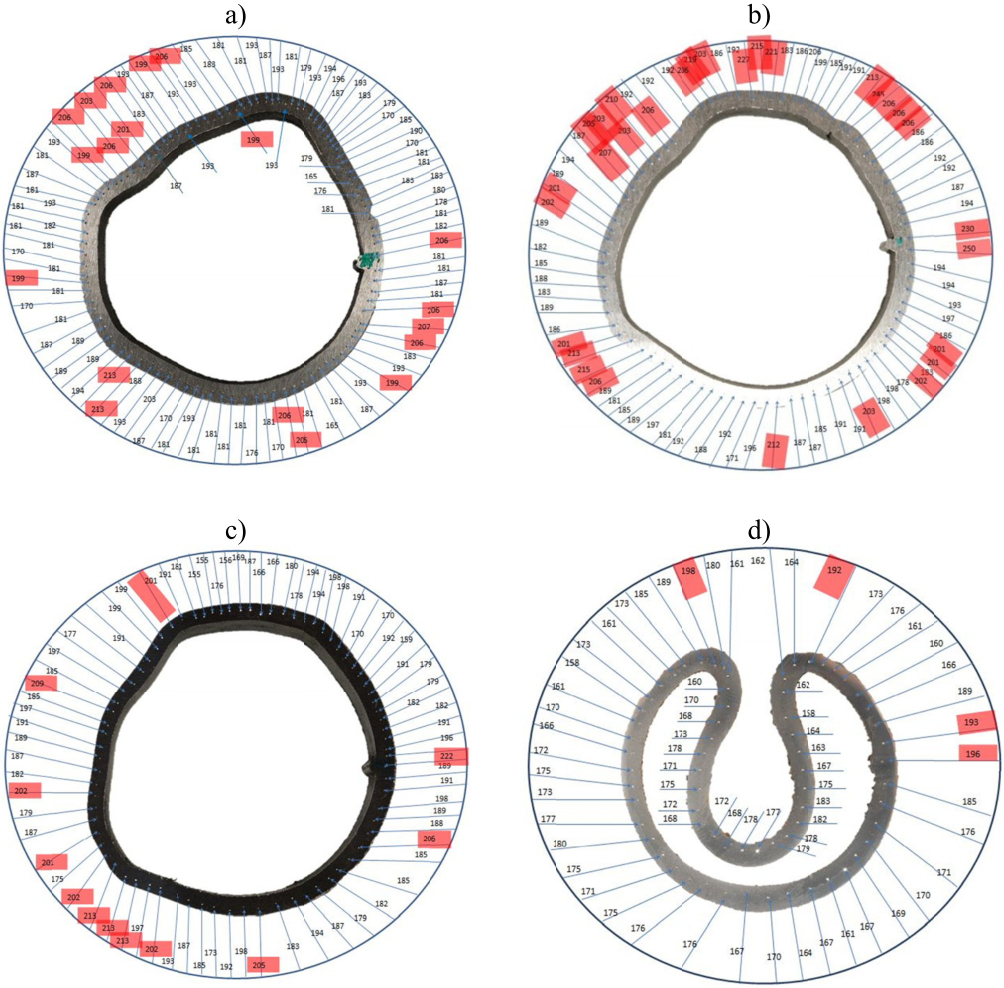

Fig. 5. A cross-section hardness distribution of the examined bolts: a) sample no 1, b) sample no 2, c) sample no 3, d) sample no 4 (not checked by the pressure test)

In Figure 3 red marked areas having a hardness higher than in the other regions of the cross-section are shown. Besides to the areas (red marked) hardened as a result of plastic deformation during the formation and expansion, increased hardness appear also in the vicinity of the longitudinal induction weld. The microstructure of investigated bolts consists of ferrite and small amount of pearlite (Fig. 6). Cold plastic deformation of initial pipe shape to obtain Swellex type rock bolt makes visible changes in its microstructure, mainly by ferrite grains elongation, as it is shown in Fig. 6b and Fig. 6c. Near the inner surface of the bolt ferrite grains are elongated in the direction perpendicular to the surface, which promotes the formation of cracks in this area.

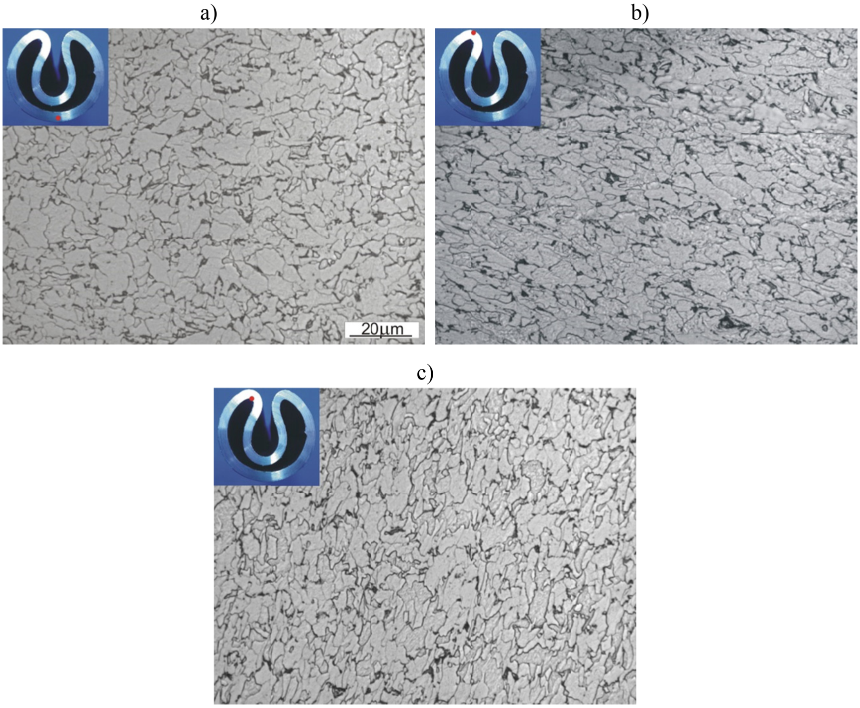

Fig. 6. Microstructure of sample no 4 in different regions (red marked): a) region of small plastic deformation, b) high plastic deformation – close to the outer surface, c) high plastic deformation – inner surface

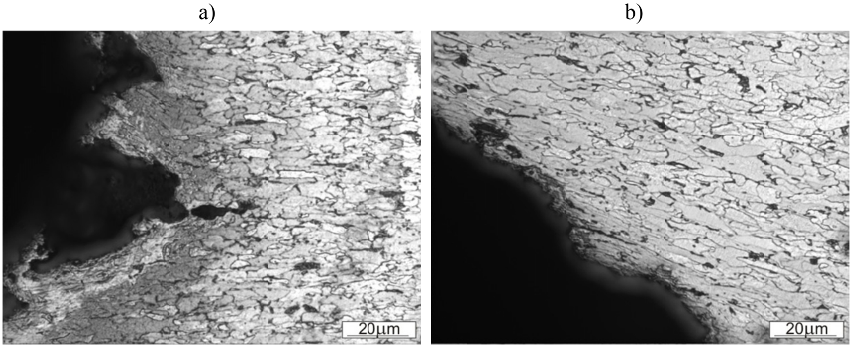

Fig. 7. Microstructure of the rock bolt (sample no 1): a) additional microcracks close to the main crack, b) main crack – decohesion path

The microstructure after bolt pressure expansion, close to the crack propagation path of sample no 1, is presented in Fig. 7, where additional microcracks are visible (Fig. 7a) as well as decohesion path, parallel to the direction of ferrite grains elongation (Fig. 7b).

Additionally, non-metallic inclusions such as long sulfides favor decohesion of the rock bolt material. For sample no 1, very long sulfide inclusions placed in the middle of the bolt wall thickness were observed in a plane parallel to the crack (Fig. 8).

For the specimens no 2 and no 3 such long sulfides as above were not observed and small nitrides inclusions were found.

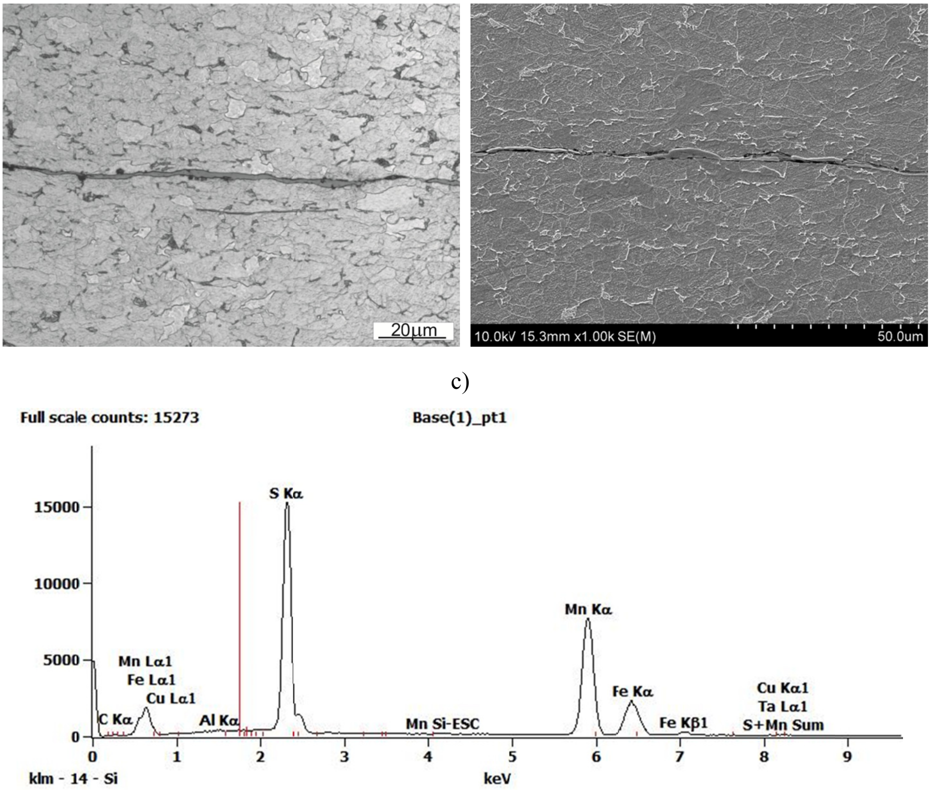
a) b) c)

Fig. 8. Sulfide non-metallic inclusion: a) light microscope, b) SEM, c) EDS analysis

## 4. Conclusions

In this study, the crucial effect of metallurgical purity and strain aging phenomenon on the possibility of the rejection of the water-expanded batch delivery by the customer is presented. On the basis of the obtained results, the following conclusions can be drawn:

- Failure of water-expanded rock bolts during the pressure test was favored by inadequate metallurgical purity – the existence of a very long non-metallic inclusions, sulfide inclusions. For special microalloyed steel that is investigated S355M steel a small volume fraction of non-metallic inclusions is required (standard does not specify the limit values of volume fraction of inclusions, it only indicates that it should be agreed in the terms of the contract). For the production of steel rock bolts, use of steel with extremely low volume fraction of non-metallic inclusions is recommended.

- The main cause of the rock bolts failure during the pressure test is the occurrence of the phenomenon of strain aging, typical for this steel grade.
- For bolts in which the chemical composition contains certain content of stabilizing elements (vanadium, niobium and titanium) strain aging after deformation is limited and either only minor cracks were observed or formed almost invisible to the naked eye microcracks on the inner surface. Effect of stabilizing elements consists of binding the interstitial nitrogen and carbon atoms in the stable nitrides (carbonitrides), which eliminates (or significantly reduces) strain ageing phenomenon.
- Reducing the risk of steel bolts failure during expansion can cause ordering S355MC grade steel with vanadium content, niobium and titanium in the vicinity allowed by the maximum content of these elements for this grade.

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*Swellex rock bolts from Atlas Copco*, Broschure presented by Cooperation of Atlas Copco Exploration and Geotechnical Engineering, Märsta, Sweden and Minova International, Melbourne, Australia, September 2009.