Experimental and theoretical assessment of functional and operational qualities of mechanical protection mechanisms used in safety couplings of drive systems of mining machines

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Abstract. Safety couplings, also called overload couplings, are used to mechanically protect the drive systems of machines – especially mining machines – against sudden overloads. Among these, couplings with shear pins are characterized by the simplest structure. The material and the diameter of the pin is selected by the designer based on the threshold moment at which the shearing should occur. The paper presents a theoretical method of selecting protective pins for specified threshold moment values for a selected Dodge® Raptor series coupling that shall find its application in the drives of mining machines (such as conveyors, crushers, pumps, etc.). Subsequently, a verification of the calculations has been performed by means of an experiment conducted on a special stand. Notable discrepancies between the results of calculations and experiments have been noted. The authors have attempted to explain that fact by testing the hardness of the pins in two planes. Incorrectly performed heat treatment of two batches of pins provided for testing has been discovered.

1. Introduction
Dynamic loads exerted on mechanical elements and assemblies as well as on the entire machine have a negative impact on their durability and reliability. The fact is especially important in case of loads exerted on mining machines and their drives, which are subject to especially heavy operational loads. The loads in concern are considerable, variable and are characterized by momentary overloads and a high frequency of machine start-ups.

To protect the drive systems of machines against overloads, safety couplings are applied (also called overload couplings). Often, safety couplings do not constitute a separate structure, but combine the properties of several other types of couplings. This may be exemplified by the coupling manufactured by KTR Polska, which combines the properties of a torsional flexible coupling and an overload coupling (figure 1).

The operation of safety couplings is based on two solutions [2]. In the first solution, a complete disconnection of the members occurs under the assumed threshold value of torque. In such case, the appropriately selected connector (usually a pin) breaks, being the weakest bearing element in the coupling and thus in the entire drive system (figure 2) [3]. The second solution consists in the application of a coupling with a mechanism limiting the transferred torque to a safe value. This group
includes e.g. friction couplings, where a relative slip occurs on friction linings between the active and passive members of the coupling during an overload (e.g. the SmartSet couplings by Voith, figure 3).

**Figure 1.** SYNTEX®-NC backlash-free overload coupling with a ROTEX® GS coupling manufactured by KTR Poland [1].

**Figure 2.** KE & ES Couplings overload coupling manufactured by Cross+Morse [3].

**Figure 3.** SmartSet coupling by Voith [4].
The key issue in safety couplings is for the disconnection of members to occur at a strictly specified torque value, with the highest possible precision of maintaining its value. In friction couplings, the value of the transferred torque is forced by the pressure of these elements, e.g. by means of a set of rings (figure 3). In case of couplings with shear pins, however, the properly selected pin (or pins) constitutes the protective element. The shear strength of the pin is dependent on its material, diameter and heat treatment. In practice, the selection of the protective pin limiting the value of the torque transferred through the coupling is not a simple matter, which will be exhibited below.

2. Selection of protective pins in shear pin couplings

Safety couplings with shear pins are usually characterized by simple structures – this is why they are often applied in machine drive systems. In such couplings, one or two pins or – less often – ribbed rods [2] are used. A higher reliability is, however, achieved with the application of one protective connector. To limit the downtime of a machine, after the coupling is activated, the connector should be easily replaceable. The \( M_{gro} \) threshold moment at which the members of the coupling should be disconnected (pin shearing) is agreed upon by the manufacturer and the designer of the machine’s drive system.

The protective pins connect the members of the coupling, thus transferring the shearing forces that are perpendicular to their axes. The \( d_o \) pin diameter is thus determined based on the shear strength condition.

The shearing of the pin will occur when the \( \tau \), shear stress exceeds the value of the \( R_t \) shear strength of the material in line with the dependence:

\[
\tau_t = \frac{F_t}{S} \geq R_t
\]

Introducing the \( S \) pin crosssection area formula:

\[
S = \frac{\pi d_o^2}{4}
\]

and the formula for \( F_t \), circumferential force per one pin in line with the dependence:

\[
F_t = \frac{2M_{gro}}{D_p n}
\]

where \( D_p \) is the pitch diameter of the pin, and \( n \) is their numer; after transformations we achieve the following dependence:

\[
d_o \leq \sqrt[4]{\frac{8M_{gro}}{\pi D_p n R_t}}
\]

The diameter of the pin may be calculated using the approximated formula:

\[
d_o = 1.6 \sqrt[4]{\frac{M_{gro}}{D_p n R_t}}
\]

In the Department of Mining Mechanization and Robotisation of the Silesian University of Technology in Gliwice, the selection of protective pins for a torsional flexible Dodge®Raptor series Raptor-SK coupling (figure 4) was conducted. The coupling is equipped with a member in which safety devices are installed in the form of pins subject to shearing at a specified value of the transferred torque. Ultimately, the coupling will be applied in mining machines such as conveyors, crushers, pumps, etc.

The E80-sized Raptor-SK coupling may be equipped with one or two protective pins distributed at the pitch diameter of \( D_p=241 \) mm. The calculations of the \( d_o \) pin diameters were made as dependent from the calculated \( M_{gro} \) threshold moment for various strength parameters of steel. Table 1 presents a list of the values of the \( M_{gro} \) calculated threshold moment, the material from which the pins will be manufactured, the \( R_t \) shear strength and the calculated pin diameters.
Figure 4. RAPTOR-SK flexible coupling with safety shear pins.

Table 1. Parameters of the protective pins.

| Material                  | Value of the calculated threshold moment $M_{gro}$, Nm | Shear strength $R_t$, MPa | Calculated pin diameter $d_o$, mm |
|---------------------------|--------------------------------------------------------|---------------------------|-----------------------------------|
| 42CrMo4 steel (50÷55 HRC after hardening) | 680                                                   | 3                         |                                   |
|                           | 1890                                                  | 5                         |                                   |
|                           | 3710                                                  | 7                         |                                   |
|                           | 7570                                                  | 800                       | 10                                |
|                           | 10900                                                 | 12                        |                                   |
|                           | 17030                                                 | 15                        |                                   |
|                           | 24520                                                 | 18                        |                                   |
| 42CrMo4-T steel (38 HRC)  | 680                                                   | 3                         |                                   |
|                           | 1890                                                  | 5                         |                                   |
|                           | 7570                                                  | 800                       | 10                                |
|                           | 12790                                                 | 13                        |                                   |
|                           | 19370                                                 | 16                        |                                   |

For the assumed values of the $M_{gro}$ threshold moment and the adopted values of strength parameters of the applied steel, the $d_o$ diameters of the pins for the Raptor coupling were calculated. Due to the fact that in many cases the reliability of the activation of the protective element at a specified torque value is extremely significant, a verification of the obtained results by an experiment may be necessary besides the strength calculations.

3. Experimental study of protective pins applied in the Raptor-SK coupling

After performing the strength calculations determining the calculated diameter, an experimental verification of the obtained results was performed for pins with the diameters referred to above. The shear strength test of the pins was conducted using a test stand (figure 5). The main element of the test stand was a special retaining and shearing tool. A strength testing machine served as a base of the test stand.

A special retaining and shearing tool (2) was installed in the strength testing machine (1) (figure 6). In the tool, the protective shear pin was fixed (3). During the tests performed with the force sensor (4), the value of the force $F$ exerted by the machine on the tool was measured (2) (the threshold value of
that force corresponds to the $F_t$ shear strength of the pin) as well as the value of the $l$ displacement of the strength testing machine was measured by means of the sensor (5). Measurement signals were transmitted to the digital A/C measurement module (6) conditioning, measuring and archiving both the measurement signals while visualizing the signals on the screen (7). The $F$ load exerted during the test was static and was increased at a fixed rate pre-set in the equipment.

The application of shear pins in a coupling limits the transferred torque to a safe value, which, if exceeded, causes the shearing of the pin and thus the disconnection of the drive. To model the process of “clean” shearing of the pin and its stable retention and fixing at the stand, a special retention and shearing tool was designed and manufactured (figure 6). The tool was comprised of a fixed housing (base) (2) to which, the pin (1) is fixed with a screw (2) on one side while being fixed to the sliding piston (3) on the other side. During the tests, the $F$ load of the piston (3) increasing to the $F_t$ threshold value, causes the sliding of the piston and thus the shearing of a given pin. The changes of the $F$ force and the $l$ displacement are measured and registered using a measurement apparatus.

![Figure 5](image)

**Figure 5.** A view of the test stand for testing protective pins, where: 1 – strength testing machine, 2 – retaining and shearing tool, 3 – protective shear pin, 4 – force sensor, 5 – displacement sensor, 5 – digital A/C measurement module, 7 – computer.

The experiments were conducted for theoretically established $d_o$ diameters of pins (table 1) made of steel for hardening and tempering. 42CrMo4 steel served the manufacturing of pins which were subsequently hardened. Two separate batches of pins were produced. The third batch was constituted of pins made of 42CrMo4-T hardened and tempered steel (table 1).

Table 2 presents the results for the pins made of the 42CrMo4 steel from the so-called “first x/I batch.” Three samples were tested for each diameter.

Figure 7a presents the view of the p7/I protective pin before the test, while figure 7b presents the pin after shearing. Figure 7b presents the location of loss of load bearing capacity and the view of the fracture.
Figure 6. The retaining and shearing tool used for shearing protective pins: a) view of the tool, b) view of the protective shear pin, where: 1 – shear pin, 2 – base of the tool (fixed housing), 3 – sliding piston, 4 – fixing screws, $F$ – force exerted on the tool, $d$ – pin diameter.

Table 2. Results of the experimental tests consisting in shearing protective pins made of 42CrMo4 steel from the first produced batch „I”.

| Pin symbol | Diameter $d$, mm | Mean value of the shearing force $F_t$, N | Mean value of the threshold moment $M_{gr}$, Nm |
|------------|-----------------|------------------------------------------|-----------------------------------------------|
| p1/I + p3/I | 5               | 17 750                                    | 2 137                                         |
| p4/I + p6/I | 10              | 66 954                                    | 8 068                                         |
| p7/I + p9/I | 15              | 147 962                                   | 17 830                                        |

Figure 7. View of the protective shear pin p7/I: a) before conducting the test, b) after the shearing of the pin.

Figure 8 presents a bar graph of the $M_{gr}$ threshold moment obtained by converting the $F_t$ force shearing the pin and the $D_p$ pitch diameter.
Figure 8. Values of the threshold moment for the tested pins, where: p1/I-p3/I pins with a diameter of 5mm, p4/I-p6/I pins with a diameter of 10mm, p7/I-p9/I pins with a diameter of 15mm.

With the exception of the pin with the diameter of 3 mm, the shearing process did not proceed correctly for this batch. As an example, figure 9a presents a view of the p4/II protective pin, while figure 9b presents the view of the p10/II pin after the loss of the load bearing capacity. The loss of load bearing capacity is understood as the shearing of the pin in its fixing part and not – as intended – in the cylindrical part.

Table 3 presents the experiment results for the pins made of the 42CrMo4 steel from the “second batch.”

Table 3. Results of the experimental tests consisting in shearing protective pins made of 42CrMo4 steel from the second produced batch.

| Pin symbol | Diameter \(d\), mm | Mean value of the shearing force \(F_t\), N | Mean value of the threshold moment \(M_{gr}\), Nm |
|------------|------------------|-------------------|-----------------|
| p1/II ÷ p3/II | 3 | 10 220 | 1 232 |
| p4/II ÷ p6/II | 7 | 31 392 | 3 782 |
| p7/II ÷ p9/II | 12 | 125 384 | 15 109 |
| p10/II ÷ p12/II | 18 | 296 471 | 35 725 |

Figure 9. View of the protective pins after shearing: a) p4/II pin b) p10/II pin.
Figure 10 presents a bar graph of the $M_{gr}$ threshold moment obtained by converting the $F_t$ force shearing the pin and the $D_p$ pitch diameter.

![Bar graph showing the threshold moment values for different pin symbols.]

**Figure 10.** Values of the threshold moment for the tested pins, where: p1-p3 pins with a diameter of 3mm, p4-p6 pins with a diameter of 7mm, p7/II-p9/II pins with a diameter of 12mm, p10/II-p12/II pins with a diameter of 18 mm.

Table 4 presents the experiment results for the pins made of the 42CrMo4-T steel from the third batch provided for testing.

| Pin symbol | Diameter $d$, mm | Mean value of the shearing force $F_t$, N | Mean value of the threshold moment $M_{gr}$, Nm |
|------------|-----------------|------------------------------------------|---------------------------------------------|
| p1/III ÷ p3/III | 3 | 6 038 | 728 |
| p4/III ÷ p6/III | 5 | 14 445 | 1 740 |
| p7/III ÷ p9/III | 10 | 61 441 | 7 404 |
| p10/III ÷ p12/III | 13 | 104 760 | 12 624 |
| p13/III ÷ p15/III | 16 | 157 428 | 18 970 |

Table 4. Results of the experimental tests consisting in shearing protective pins made of 42CrMo4-T steel from the third produced batch.

Figure 11 presents the view of the p14/III protective pin after shearing. The fracture was formed in the correct location, that is in the cylindrical part of the pin.
Figure 11. View of the p14/III protective shear pin.

Figure 12 presents a bar graph of the $M_{gr}$ threshold moment obtained by converting the $F_i$ force shearing the pin and the $D_p$ pitch diameter.

As it may be noted in figures 8, 10 and 12, the values of the threshold moment for each of the tested diameters were comparable. The highest difference in the values occurred for the smallest diameter of the pin (3 mm) and reached nearly 23%. The relative difference was decreasing along with the increase of the diameter. For the diameter of 18 mm it amounted to only 1%.

Figure 12. Values of the threshold moment for the tested pins, where: p1/III-p3/III pins with a diameter of 3 mm, p4/III-p6/III pins with a diameter of 5 mm, p7/III -p9/III pins with a diameter of 10mm, p10/III -p12/III pins with a diameter of 13 mm, p13/III-p15/III pins with a diameter of 16 mm.

4. Comparative analysis of the calculation results and the results of the experimental study of the protective pins

Figure 13 presents a comparison of the calculated values of the $M_{gro}$ threshold moment and the mean values of the $M_{gr}$ threshold values obtained in the test of the samples from the first batch with diameters of 5, 10 and 15 mm.
Figure 13. Comparison of the calculated threshold moment values and the values obtained for the tested first batch samples.

Figure 14 presents a comparison of the calculated values of the $M_{gro}$ threshold moment and the mean values of the $M_{gr}$ threshold values obtained in the test of the samples from the second batch with diameters of 3, 7, 12 and 18 mm.

Figure 14. Comparison of the calculated threshold moment values and the values obtained for the tested samples from the second batch.

Figure 15 presents a comparison of the calculated values of the $M_{gro}$ threshold moment and the mean values of the $M_{gr}$ threshold values obtained in the test of the samples from the second batch with diameters of 3, 5, 10, 13 and 16 mm.

As it may be noted, the values of the converted $M_{gr}$ threshold moment obtained based on experiments (pin shearing) for the first and third batch are higher than the calculated $M_{gro}$ threshold moment. In case of the third batch, the situation is opposite.
Figure 15. Comparison of the calculated threshold moment values and the values obtained for the tested samples from the third batch.

In case of the first and third batches, the differences in the results are slight and reach 12% at most. In case of the second batch, the difference is significant and reaches 31%. The author has made an attempt to identify the reason for the above in the further part of the paper.

5. Protective pin hardness measurement
As an attempt to explain the causes of the differences in the values of the shearing force and the irregular shearing process in case of the second batch provided for testing, hardness tests were conducted to confirm the quality of the hardening process. The hardness testing was conducted for a selected sample of a given batch, using the Vickers method. Figures 16 and 17 present the mean results of the hardness measurements performed in longitudinal and transverse sections of the pin.

Figure 16. Hardness test performed for the longitudinal section of samples, where: p1/I – first sample from the first batch, p2/II – second sample from the second batch, p10/III – tenth sample from the third batch.

The highest hardness was measured in case of the sample p1/I (mean value of 600 HV, figure 16). The lowest hardness, on the other hand, was measured for the sample p10/II (mean value of 294 HV, figure 16).
The hardness measurements of the samples, both in the longitudinal and transverse sections, have exhibited significant differences. The highest value in case of the sample p1/I was measured in testing the longitudinal section (a difference of 9.4%). The highest value in case of the sample p2/II was measured in testing the transverse section (a difference of 3.4%). The situation was similar in case of sample p10/III (a difference of 18.8%).

Analyzing the hardness values in longitudinal sections, a high divergence was observed. The highest value was measured for the sample p1/I and the lowest for the sample p10/III (a difference of 51%). A similar phenomenon was noted for the transverse section, in case of which, however, the difference was 36%.

As mentioned above, the first two batches were manufactured using 42CrMo4 steel, which was subsequently hardened and tempered to achieve a hardness of 50-55 HRC. The third batch, on the other hand, was made of hardened and tempered 42CrMo4-T steel with an assumed hardness of 38 HRC.

The assumed hardness of the pin was achieved for the sample p1/I in the longitudinal and transverse sections, while in case of the sample p10/III the assumed hardness was only achieved in the transverse section, which may have testified of the improper hardening of the rod which was used for the production of the pins. In case of sample p2/II, a value significantly lower than the required was measured for both of the sections. This indicates an incorrect process of hardening and tempering.

6. Summary
Couplings with destructible connectors are the simplest protection of drive systems against overloading. In case of the Raptor-SK coupling, the connectors are in the form of a cylindrical pin with two fixing surfaces.

The calculation of the diameters of the shear pins for given threshold moments and the conducted experiments have indicated that:

- a difference exists between the values of the $M_{gro}$ calculated values of the threshold moment and the $M_{gr}$ values obtained in tests. The highest difference was exhibited by the second batch of pins and the lowest in case of the third (figure 8, 10, 12);
- higher values of the $M_{gr}$ threshold moment were observed in case of results obtained in tests of the first two batches of pins (figure 13, 14);
- based on the experiments, comparable values of the threshold moments were obtained for each of the pin diameters and batches (figure 8, 10, 12);
a significantly lower hardness value was measured for the second batch of the pins, as compared to the required value, which indicates an incorrect thermal treatment process;

- in case of the third batch of pins, a hardness value lower than required was measured for the longitudinal section, which exhibits the incorrect hardening of the rod material which was used for the production of protective pins.

As mentioned above, the shearing proceeded incorrectly (with the exception of the 3 mm pins) in case of the second batch of the protective pins (figure 9). In case of the diameters of 12 and 18 mm, the shearing during the test on the test stand occurred at a significantly lower $F_t$ shearing force ($M_{tr}$ threshold moment) than indicated by calculations. The conducted hardness test of the samples from that batch did not provide answers regarding the irregular shearing process. The achieved hardness levels were notably smaller than assumed, while the manner of breaking suggests an opposite irregularity. Due to the above, it is necessary to conduct further research aimed at explaining the causes of the shearing process proceeding in such a manner.

In conclusion of all the analyses conducted within the study, it may be stated that besides the theoretical calculations, also verification tests should be conducted, especially in cases of applications of these couplings (equipped with protective pins) in machines of key importance – particularly in the mining industry.

7. References
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