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Technological aspects of mining chain production development

This paper presents a brief historical overview of the development and types of mining chains currently in production, as well as their contribution to the global market. The directions of development for mining link chains were identified in terms of the materials and strength parameters applied. The negative influence of certain factors that decrease the performance of mining chains are also demonstrated.

Key words: *chain, safety, durability*

1. INTRODUCTION

The first examples of link chain applications in mining are known from the comprehensive work published in 1556 by Georgius Agricola, titled *De Re Metallica Libri XII*. Book six includes numerous illustrations (Fig. 1) depicting link chains used primarily in vertical bucket elevators intended for pumping water out of underground mines [1, 2].

Link chains replaced hemp ropes which were formerly widespread, but which would quickly decay in damp shaft workings and lose their load capacity. However, the application of chains presented a different disadvantage: damage to a single link would often result in chain failure. Falling chains damaged the structure and lining of shaft ways [3], which ultimately led to the invention of steel ropes in the 19th century.

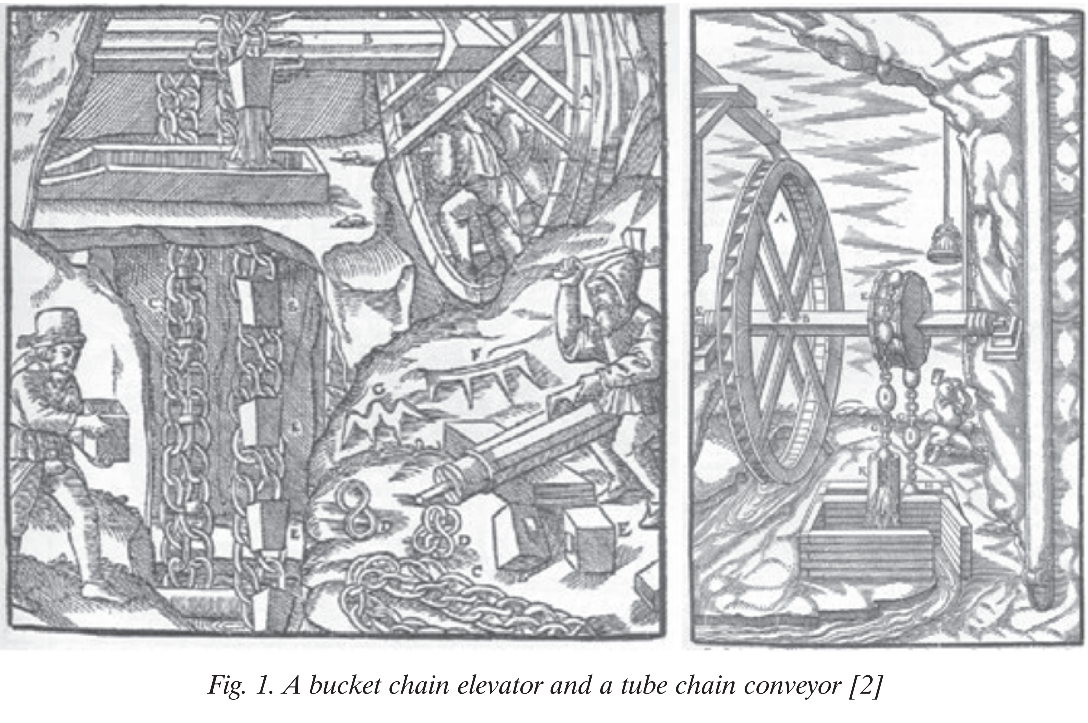

Fig. 1. A bucket chain elevator and a tube chain conveyor [2]

Link chains only saw a resurgence in mining after the introduction of electric link welding – which considerably lowered the production costs and increased the weld quality – and together with the mechanisation of mining processes, particularly with the advent of longwall technology for hard coal deposit extraction.

2. MINING CHAIN DEVELOPMENT

The mechanisation of material transport in hard coal mining began in the 1920s by means of vibrating conveyors, also known as shaker conveyors. The first conveyor utilising a link chain was introduced into mining practice in 1932. It was a retarding disc conveyor, used at inclinations of over 18° (Fig. 2). The purpose of the discs mounted on the chain was to impede the movement of the material rolling down open troughs. Vibrating conveyors and disc conveyors used underground were gradually replaced by chain conveyors [4, 5].

Fig. 2. Retarding disc conveyor

The first chain conveyors were equipped with roller chains, depicted as a diagram in Figure 3 [6]. Such a chain type hindered the relocation of the conveyor, as it allowed the trough track to be bent only in the vertical plane, therefore later conveyor designs began to utilise link chains in the form of strands with double outer chains [7]. Initially, these were chains obtained from the shipbuilding industry, e.g. 16 × 64 mm, i.e. with a pitch equal to four times the diameter, $t = 4 \cdot d$. To increase the conveyor reliability, the chain diameter was increased to 18 mm while retaining a pitch of 64 mm. The chain pitch was retained to preserve the pitch diameter of the drive sprockets and prevent the need to change the drive constructions. On the other hand, the link diameter of 18 mm was the greatest diameter at the time that could be obtained by electrical resistance welding. Only the introduction of flash butt welding in 1952 [6] made it possible to weld chains with greater diameters by means of electric welding. The first longwall chain conveyor equipped with a link chain was tested in the "Bobrek" mine in Upper Silesia, known at the time as "Gräfin-Johanna-Grube", in 1941 [8, 9].

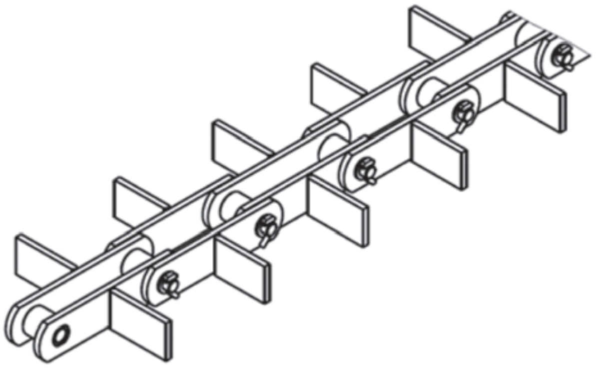

Fig. 3. Example diagram of a roller chain [6]

The demand for hard coal increased after World War II, consequently starting the era of mechanisation in mining. Chains applied in chain conveyors saw a rapid increase in demand, which led to the drafting of the first standard concerning "mining chains", DIN 22252. Its first edition of March 1951 [10] described only 16 × 64 mm and 18 × 64 mm chains.

Initially, mining chains were manufactured in strands of 15 links. The length tolerance was regulated by the standard (+4 mm / –1 mm). It was technologically impossible to produce strands of precisely same length in repeatable series, therefore the 15-link strands were measured and sorted according to the length deviation and subsequently tied into pairs. The pairing of strands with the same length deviation was a result of the using outboard chain assemblies. A typical chain assembly section consists of 2 chain strands, 2 outboard connectors, and 1 scraper (Fig. 4). Depending on the needs, such sections would be combined into series of typical length, e.g. about 10 m, which usually varied based on the logistical capabilities of the user.

Fig. 4. Outboard chain assembly [11]

The development of mining chains was a consequence of increased extraction intensity and the related increased capacity of mining chain conveyors. To increase their operational parameters, the chains were manufactured with gradually increased diameters (∅20, 22, 24, 26 and 30 mm) and progressively better grades of steel [2]. The fourth edition of standard DIN 22252 of December 1973 [12] describes chain sizes that are still in use to this day, e.g. 22 × 86 mm, 24 × 87.5 mm, 26 × 92 mm and 30 × 108 mm. The 30 × 108 mm chain was the largest mining chain at the time as well as the first one to be manufactured in long strands and used as a central chain. Initially, the 30 × 108 mm chain was used as a single central chain, but after the calibration and pairing process was improved, it was also used as a double central chain [13]. The standard [12] introduced a length difference tolerance for strands with lengths of up to 25 m. For a pair of chains, the permissible length difference of both strands was up to 8 mm. The Polish standard PN-G-46701:1997. *Mining link chains* [14] permits a length difference under a test load no greater than 0.15% of the link pitch sum for long chains. Figure 5 presents the history of nominal diameter development for mining chains.

The first type of flat chain was introduced on the market in 1985 [9]. It was a chain with a nominal diameter of 38 mm. All the subsequent chains with greater nominal diameters were flat type chains (Fig. 6), super flat chains or special chains [15]. The 42 × 137 mm plough chain is an exception in this series, as it was introduced in the form of a regular link chain in 2006. Among the special chains, noteworthy cases include compact chains put into production in the 1980s, whose nominal diameter refers to the horizontal link, whereas the vertical link diameter differs along the link circumference and is typically greater at the bends than the horizontal link diameter. A unique design case includes triple flat chains, whose nominal diameter typically refers to a theoretical computational cross-section. The dates provided in Figure 5 are only approximate, as it is difficult to unanimously declare what should be deemed the date of introduction for a new nominal chain size: the date of the construction design, the patent application, the determination of the manufacturing technology, the first underground use or the inclusion in a standard.

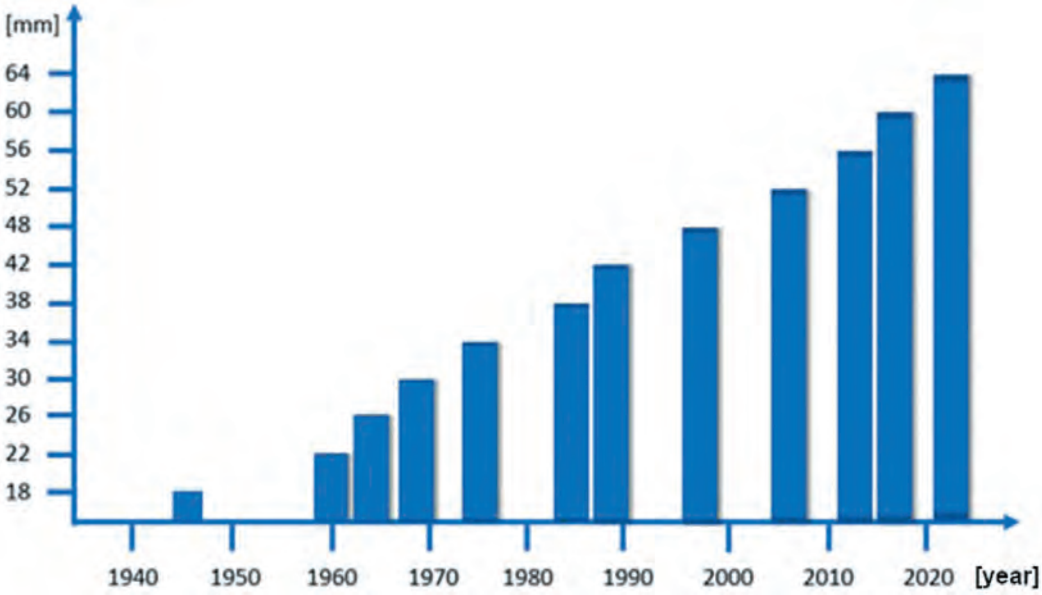

Fig. 5. History of nominal mining chain diameter development

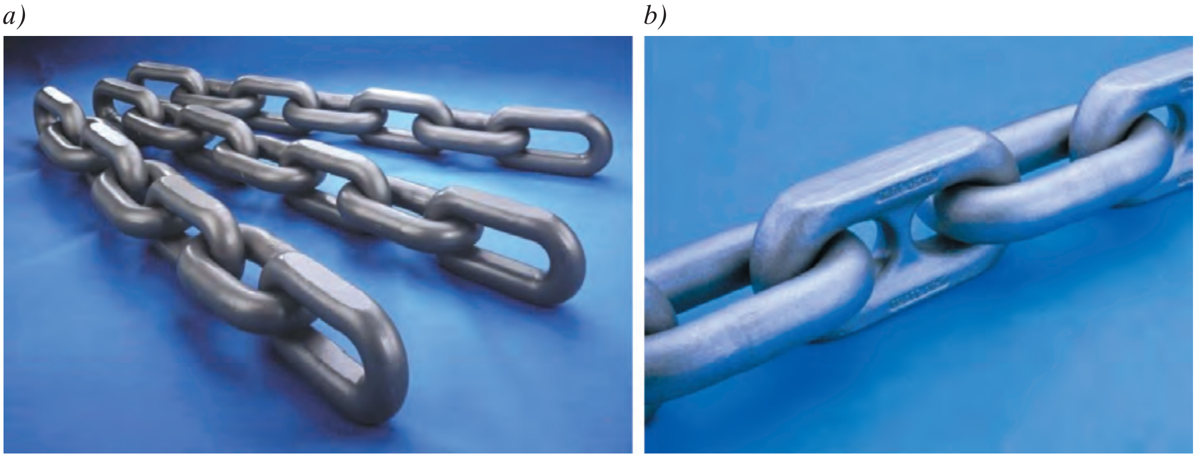

Fig. 6. Chains: a) flat; b) super flat

3. INFLUENCE OF MATERIAL PROPERTIES ON CHAIN PRODUCTION TECHNOLOGY

At the start of the mechanisation period, chains used in mining machines were often still forge welded, i.e. heated in a forge hearth or furnace and forged manually using a hammer. The weld was at the bend, as the welding involved sharp and overlapping bar ends. Welds performed in such a manner did not meet the growing technical needs of the users. The application of resistance welding made it possible to improve the quality of the weld, although its use was limited to links with a bar diameter of 18 mm [6]. Nevertheless, even for mining chains manufactured in this manner, the low quality of the weld was one of the primary reasons for chain failure. Only the introduction of flash butt welding in chain production in 1952 made it possible to significantly improve weld quality. Flash butt welding enabled the development of chains with nominal diameters exceeding ∅18 mm. A stable evolution within the scope of chain production can be witnessed since 1940. Market demands resulted in the manufacturing of chains with greater diameters as well as successively increased properties of >900, 1000, 1050, 1100 MPa, which are characterised by significantly higher operational parameters compared to chains per PN and DIN. The application of new materials and heat treatment technology made it possible to achieve an optimal and repeatable hardness distribution in each link, as well as to obtain variable hardness in a single link, that is hard bends and plastic straight sections with lower hardness. The type of the applied material and treatment method changed accordingly in successive years, as per the data presented in Table 1.

Currently, the most popular grade of steel used for mining chain production is 1.6758 per the German steel code, that is 23MnNiMoCr54, whose Polish counterpart is called 23G2NMHA. Lower grade steel is often used for chains with link diameters of up to 26 mm, i.e. 23MnNiMoCr52, number 1.6541, whose Polish counterpart is called 23GNMHA. Currently, chain manufacturers utilise the 1.6758 grade of steel with certain modifications concerning the chemical composition.

The chemical composition of the most popular grade of steel used for mining chain production is provided by the relevant standard [16]. The Polish standard [14] does not impose a specific grade of steel on manufacturers. In order to fulfil the requirements of clients in terms of chain strength, fatigue life and the appropriate corrosion protection, chain manufacturers use toughened versions of steel. The publication [17] presents the sample chemical compositions of a 42 × 137 mm plough chain produced by three different companies (Fig. 7).

Table 1

Type of material and heat treatment

1945	1950	1968	1974	1985	1990	1997
St-35.13K	15Mn3	20MNCr4	23MnNiCrMo64	23MnNiCrMo54	23MnNiCrMo54	23MnNiCrMo54
Natural hardening	Hardening	Hardening and tempering	Hardening and tempering	Hardening and tempering	Double quenching >Ac3	Double quenching >Ac3

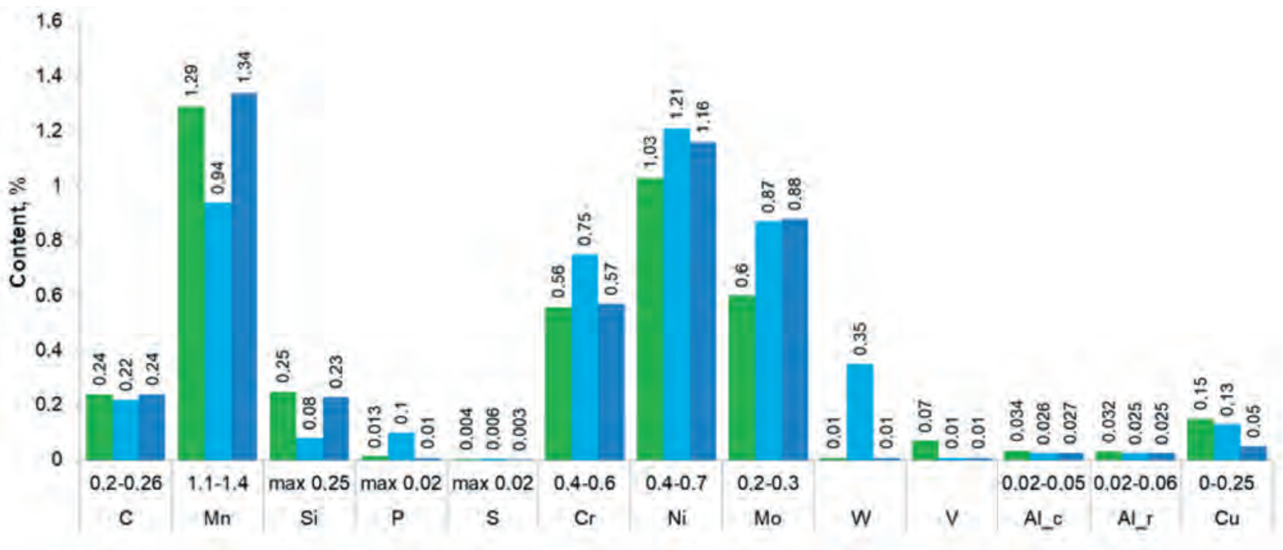

Fig. 7. Example chemical composition of steel

Certain mining chain manufacturers strive to introduce grades of steel on the market that are further improved with the micro-additions of other metals, e.g. wolfram, vanadium, boron and so on. The purpose of these practices is to obtain parameters of steel after heat treatment that would improve the mechanical properties of the mining chains, particularly their impact resistance.

3.1. Influence of material properties on the weldability of steel

The advancements in welding technology led to the development of steel used to form the mining chains. Initially, this included carbon steel (unalloyed), later steel with manganese additions, and only by the end of the 1960s would chain production begin to involve low-alloy steel with manganese, nickel, molybdenum and chromium additions. The first standard describing low-alloy steel for mining chain production was published in 1965. It was the German standard DIN 17115 [18]. Its Polish counterpart is standard PN-89/H-84023/08 [19].

A significant parameter for evaluating the suitability of a given grade of steel for mining chain production is the carbon equivalent C_e. It is a parameter used in welding that expresses the weldability of carbon and low-alloy steel depending on the chemical composition of the steel. It characterises the propensity of a material for developing welding cracks. The carbon equivalent is determined per formula (1) [11]:

$$C_e = \mathrm{C} + \frac{\mathrm{Mn}}{6} + \frac{\mathrm{Cr}+\mathrm{V}+\mathrm{Mo}}{5} + \frac{\mathrm{Ni}+\mathrm{Cu}}{15}\ \% \qquad (1)$$

The lower the C_e, the greater a material's weldability. It is assumed that the carbon equivalent also expresses a material's suitability for flash butt welding. Critical carbon equivalent values for flash welding diverge from those acknowledged for fusion welding and are determined experimentally, which is related to the heating temperature and the diameter of the welded bars. It is assumed that flash butt welding can be performed without risk of cracking up to a value of $C_e = 0.8$, whereas the limit for the carbon equivalent for welding is $C_e < 0.9$ [11]. Contaminations, particularly the sulphur and phosphorus contents, also have a significant influence on the weld quality and a material's capacity for welding. Their combined content should not exceed 0.035%. Aluminium and copper are also undesirable alloying components.

3.2. Influence of material properties on chain galvanisation

The problem of mining chain corrosion was solved by the introduction of hot-dip galvanisation, also known as hot dipping, as the zinc is applied on the chain links by means of a several minute long bath in liquid zinc at a temperature of about 440–460°C. During this bath, the zinc atoms undergo diffusion into the crystalline structure of the steel [20], and the surface irregularities and pores are filled with zinc, which generates a layer which strictly adheres to the chain link surface, known as a zinc and steel (zinc-iron) alloy, with a thickness of about 80–120 μm. The coating is characterised by greater adherence to the base and relatively high abrasion resistance.

The quality of the obtained zinc coatings (lustre, smoothness, thickness, adherence etc.) varies and depends on the chemical composition of the steel, particularly on the carbon (C), phosphorus (P) and silicon (Si) contents. The combined carbon and silicon content in the steel should not exceed 0.5%. For steel containing carbon in the form of martensite, an increase in carbon content within 0.01–2.08 wt% systematically increases the reactivity of steel relative to the liquid zinc without extending the linear range of the reaction course. For steel containing silicon, the zinc and iron reaction may proceed with particular intensity, and the contribution of the zinc-iron alloy in the coating will be greater than usual. In extreme cases, the zinc coating may consist completely of the zinc-iron alloy. This phenomenon (known as the Sandelin effect) is observed particularly at silicon contents within 0.03% to 0.14% as well as above 0.25%. In such cases, the zinc coating is typically dull grey, rough, non-uniform and brittle – vulnerable to deformations and mechanical damage. The influence of the silicon content on the solubility of steel in liquid zinc is presented in Figure 8 [21]. The silicon used in steelmaking leads to a major increase of its reactivity with liquid zinc, which is particularly high at two concentrations of this element, amounting to about 0.1 wt% and about 0.4 wt%.

The zinc coating properties related to the chemical composition of steel are defined in the relevant standard [22]. Therefore, considering the silicon and carbon contents in steel for chain production, the criteria describing the suitability of steel for hot galvanisation can be defined as follows:

$$C + Si < 0.5\% \tag{2}$$

$$0.1 < Si < 0.25\% \tag{3}$$

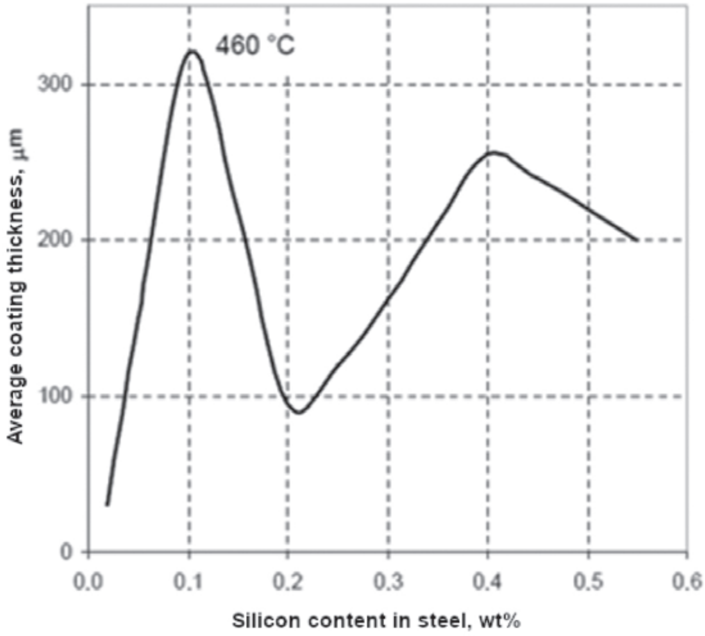

Fig. 8. Influence of silicon on the coating thickness

3.3. The influence of link manufacturing technology on chain strength parameters

For many years, the direction of chain conveyor development has entailed the utilisation of chains formed from thicker bars, better materials and with improved ductility. Initially, experience from mines in western European countries with advanced coal mining demonstrated the validity of this concept. For example [23], in 1983 in France it was shown that a correctly made and selected 26 × 92 mm chain strand could be used to safely transport 0.6–0.8 Mt of coal under difficult geological and mining conditions, whereas a 34 × 126 mm chain strand could be used for as much as 2.4 Mt of the extracted material. This direction of development led to the production of conveyors with 60 × 189/136 mm chain strands that should be expected to provide even better results. The chart (Fig. 9) presents the progression in the diameter and breaking load values since 1940. As displayed, since 1940 the bar diameter has increased from 16 to 60 mm, while the break load is now 4760 kN.

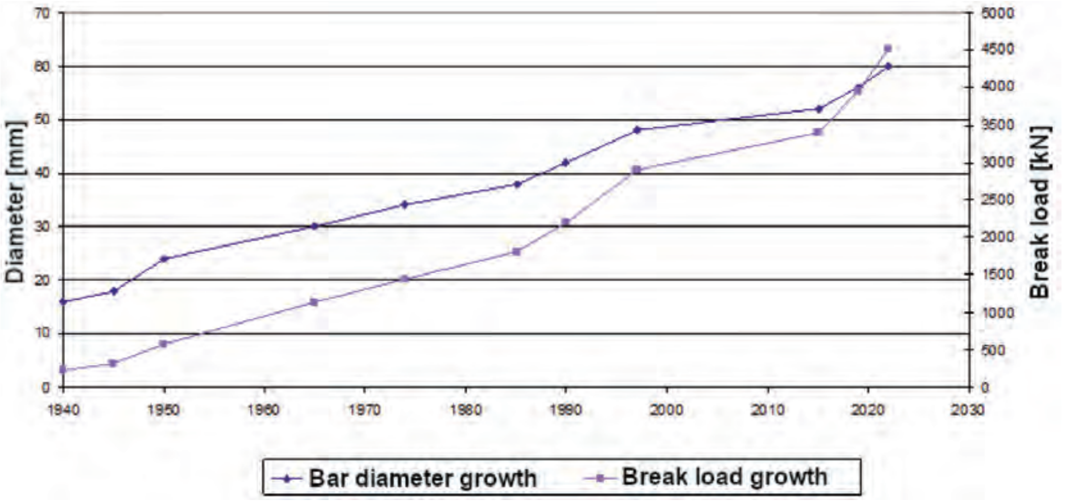

Fig. 9. Strength and geometric parameter progression

3.3.1. Influence of heat treatment on impact resistance

The strength of the steel for chain production has a direct influence on the mining chain quality class, and it depends on the applied heat treatment. A critical step of the multi-stage treatment process, one which determines the final strength parameters, is tempering. In order to identify the relationship between the impact resistance and the tempering temperature of steel for chain production, a series of comparative tests were performed, which compared samples of 1.6758 steel from four suppliers: A, B, C and D. Figure 10 presents the results of all the tests in the form of charts.

This can best be seen on the example of supplier A that at a temperature range of about 350°C the impact resistance results reach the local minimum, which corresponds to the tempering temperatures of class D chains. High impact resistance values are obtained at tempering temperatures above 450°C, and it is class C chains that undergo tempering at such temperature ranges.

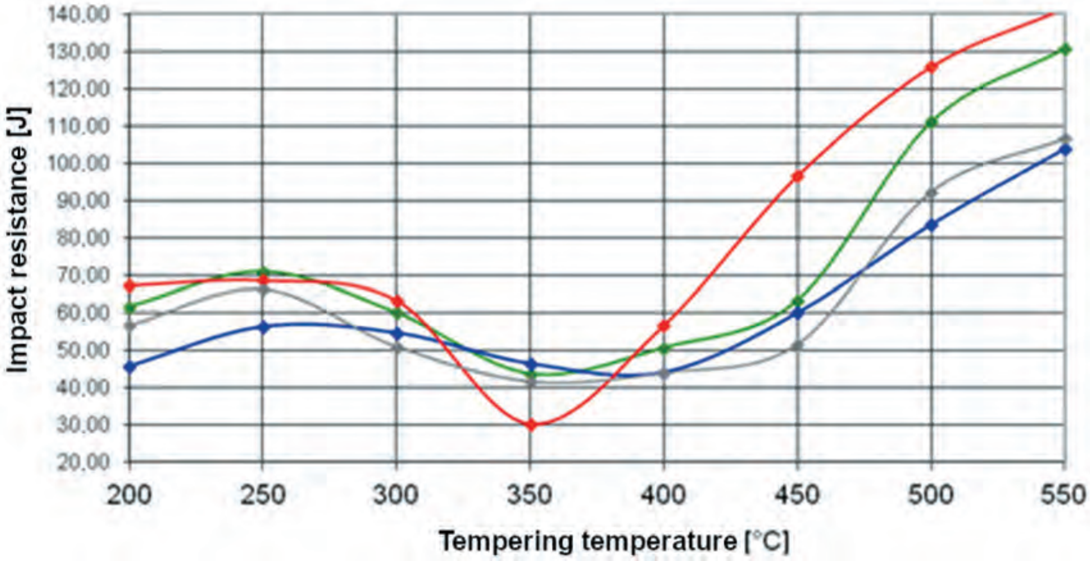

Fig. 10. Test results for impact resistance relative to tempering temperature for steel samples from suppliers A, B, C and D

3.3.2. The influence of the galvanisation process on strength parameters

Experimental tests described in [23] confirmed that hot-dip galvanisation decreases the mechanical properties of high-strength grades of steel as a result of the additional tempering of the martensitic structure. The key advantage of such steel is the high strength of the material (ductility and tensile strength). Steel with high silicon, chromium, molybdenum, and manganese content is characterised by high hardness together with high strength. It has a high yield point as well as tensile strength. In the case of this type of steel, the change in the yield point and tensile strength resulting from the hot-dip galvanisation will be considerable. The tests conducted as part of the publication [24] noted a decrease in tensile strength by 17%, whereas 14% was the result obtained as part of the publication [25]. The results described in these works confirm that high-strength steel is only suitable for hot-dip galvanisation when the degree of the strength parameter reduction is known.

4. ANALYSIS OF THE SIZE AND DESIGN OF MINING CHAINS USED IN THE INTERNATIONAL MINING INDUSTRY

The general trend to use increasingly higher nominal mining chain diameters finds confirmation on the example of the volumes produced by one of the leading mining chain manufacturers [26]. The data displayed in Figure 11 is not representative for the total global production, but it nevertheless provides an idea of the approximate percentage contributions of the individual sizes. Periods when specific sizes would dominate the production can be observed when analysing the individual mining markets. On the example of the American market, it can be concluded that the machinery undergoes modernisation about every 10 years, which is followed by a transition to another size of mining chains used in longwall conveyors. In the 1980s, 34 × 126 mm link chains were the most popular in the USA, before they were supplanted by flat 38 × 126 mm chains. After the year 2000, flat 42 × 146 mm chains were the most commonly applied, whereas after 2010 the market was dominated by chains with a link diameter of 48 mm. Currently, the authors are aware of existing installation modernisation projects aimed at applying chains with a nominal diameter of 52 mm.

The intensification of the production in longwall faces combined with increasingly greater conveyor chain sizes results in an increase of the chain life, measured in tons of transported material, which amounts to a gross weight of 10–12 million tons of material in the case of chains with a nominal diameter of ∅48 mm.

In terms of their performance, the mining chain life is primarily limited by the operational conditions, i.e. the coal production intensity, the rock content, the mining conditions, and particularly the prospective occurrence of corrosion, and amounts to 12–24 months regardless of the size and type of the chain.

At the same time, a trend can be observed towards utilising increasingly flatter chains, as a result of adapting their design to the limited dimensions of chain conveyors with the simultaneous increase in the installed electric motor power. The relatively small contribution of triple flat chains visible in Figure 12 is a consequence of their high costs of production and the patent restrictions that limit the possibilities of their circulation. The percentage contribution of specific mining chain types and sizes on individual markets depends on the extraction intensity, the development level of the mining technology and the financial capabilities of the local coal producers.

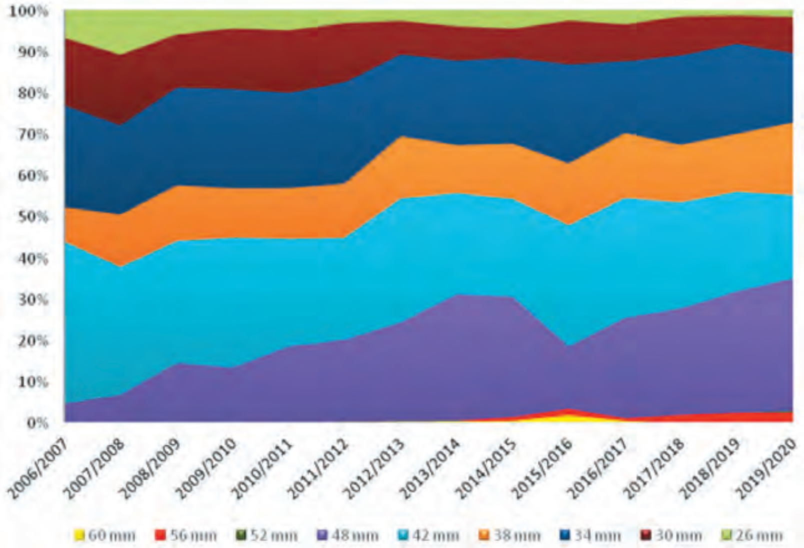

Fig. 11. Percentage contribution of individual mining chain sizes [27]

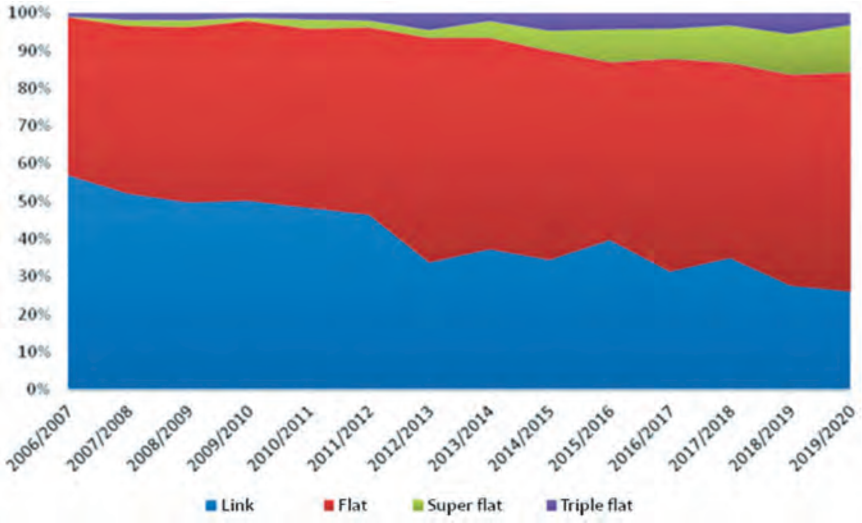

Fig. 12. Percentage contribution of individual mining chain designs on the example of a mining chain manufacturer's overall production [27]

5. CONCLUSIONS

This paper contains a summary of laboratory testing results and the literature review conducted. The first link chains used in mining machinery had a diameter of 16 mm. The smallest chains used in mining conveyors are 14 × 50 mm, whereas the biggest chains that currently find application in such conveyors have a nominal diameter of 60 mm. Development work is already being conducted on next-generation chains with nominal diameters of 64 mm and ∅68 mm. The trend towards increasing the chain diameters has been going on for nearly the last 80 years of mining machinery history, even though it had appeared like a technical limit regarding their production was reached several times already. It also seemed that the application of increasingly greater diameters would not be necessary due to the installation of increasingly powerful motors in chain conveyors and ploughs in order to improve their efficiency. The presented information demonstrates that not every material or type of heat treatment can be used indiscriminately in chain manufacturing. The development of new grades of high-strength steel had a significant influence on the advancements in chain production. Apart from improving the mining chain load-bearing capacity as a consequence of the increased link diameters, the work of the designers and technologists was focused on the following goals:

- to increase the chain strength following the application of new grades of steel,
- to unify the mechanical parameters through precise heat treatment,
- to decrease the vertical link height in combined chains, enabling chain conveyor height reduction,
- to extend chain life by designing links of shapes enabling the slower elongation of chain pitch,
- to obtain repeatable link shapes, particularly in terms of their pitch.

The current trend in development is to design chains equipped with load measurement sensors enabling constant load monitoring as well as chain pretensioning control and protection against overloads following the excessive loading or jamming of the conveyor. Work in this scope is being conducted by several research and development centres associated with chain conveyor producers as well as chain manufacturers. Integrating force measurement sensors in a moving conveyor chain is a difficult technical challenge due to the technological barriers pertaining to both the miniaturisation of the measuring system as well as the power supply and the capabilities for measurement data transformation.

Hard coal production by means of longwall mining will remain a major part of the global production of this resource over the next two decades. Given the increase in efficiency and the need to monitor production in order to improve extraction safety, the continued development of the designs and sizes of mining chains should be expected, while the levels of their current demand will remain the same on a global scale.

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