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INNOVATIVE ZINC ALLOY FOR PRODUCTION OF POSITIONERS OF CAR WINDOW ACCESSORIES

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INNOVATIVE ZINC ALLOY FOR PRODUCTION OF POSITIONERS OF CAR WINDOW ACCESSORIES

INNOWACYJNY STOP CYNKU DO PRODUKCJI POZYCJONERÓW OSPRZĘTU SZYB SAMOCHODOWYCH

***Summary**: The present paper is related to the problems of production of car window accessories from the modified foundry alloys of zinc. The material includes the results of the conducted industrial tests and developmental work. The range of the requirements for components and the properties of standardized materials were discussed. The innovative method for titanium alloying in the zinc ZnAl4Cu3 alloy was developed and described. The casts made from innovative materials, as produced in the demonstration line were subjected to a series of endurance (fatigue) tests.*

***Keywords**: positioners, car windows, zinc alloy, titanium, pressure casting*

***Streszczenie**: Artykuł dotyczy zagadnienia wytwarzania pozycjonerów osprzętu szyb samochodowych ze zmodyfikowanych stopów odlewniczych cynku. Materiał obejmuje wyniki przeprowadzonych badań przemysłowych oraz prac rozwojowych. Przedstawiono zakres wymagań stawianych komponentom oraz właściwości znormalizowanych materiałów. Opracowano oraz opisano nowatorską metodę stopowania tytanu w stopie cynku ZnAl4Cu3. Wytworzone w ramach linii demonstracyjnej odlewy z innowacyjnego materiału podano szeregowi badań oraz testom zmęczeniowym.*

***Słowa kluczowe**: pozycjonery, szyby samochodowe, stop cynku, tytan, odlewanie ciśnieniowe*

Introduction

Zinc alloys have many different applications in the car industry due to their properties which make that they are an attractive choice for many projects. They are often used in production of decorative elements inside and outside the vehicles where they are a perfect basis for coatings such as chrome plating. Such operation may include internal details such as door handles, knobs, dashboards elements and, also, external elements such as frames of windows or decorative elements on the car body. Due to the easiness of casting and good mechanical properties, zinc alloys may be employed in production of door locks, keys, regulation mechanisms and other elements connected with functioning of vehicle. The mentioned above alloys may be also applied in production of different electric and electronic elements in cars. They may include connection housing, fixing elements for conduits or shields of many types. Owing to their endurance, zinc alloys may be used in production of housing and protection of car elements such as sensors, transmitters or electronic modules. They may be also used in manufacture of different mechanical components which are not subjected to a great loading such as housing for engines of the car wipers, suspension parts or the elements connected with the exhaust system.

It should be noticed that the choice of zinc alloys in the car industry is dependent on the specified requirements for each component and the manufacturing costs. The alloys of zinc offer such profits as a perfect capacity of casting, good finish of surfaces, low melting temperature and favourable mechanical properties in the respective applications. However, due to a relatively low mechanical endurance as compared to certain other materials, it is mainly used in the sites where the dynamic or strength loading does not occur. Nevertheless, there are developed the methods for the increase of the casting strength of zinc alloys via thermal treatment or by alloying.

The increase of mechanical casting properties of zinc alloys

Owing to their favourable casting and utility properties, foundry zinc alloys are employed in a wide range. They demonstrate a low melting temperature any, consequently, a low casting temperature and good castability. They are especially suitable in casting under the pressure. The main alloy additives in zinc alloys include aluminium and copper. The small quantities of magnesium, manganese, iron, nickel and titanium are also introduced to zinc alloys. Aluminium prevents from solving of iron in the alloy, increases strength and improves castability of the alloy. Moreover, aluminium affects the anti-friction qualities. The lowest consumption is observed in alloys, containing ca. 5% Al and those ones with the content of aluminium in the limits of

14–30%Al. On the other hand, at the increased pressure of the order of 490 MN (50 kG), the lowest consumption occurs in the alloys with 14–26% Al content. Copper in the zinc alloys causes the increase of the inclination to spontaneous ageing; it affects, however, the increase of the strength, hardness and resistance to corrosion. In the alloys cast to metal moulds, the maximum tensile strength of Zn-Al-Cu alloys occurs at the 3.5–4.5% copper content. Hardness of alloys cast to sand as well as metal moulds is almost equal and is proportionally increased together with the increase of copper content, reaching value of ca. 90 HB at the addition of 5% Cu content. Copper added in the amount of 1–3 % decreases the inclination Zn-Al-Cu alloys to intercrystalline corrosion. The higher additives of copper increase the sensitivity of Zn-Al alloys to ageing and the related dimensional changes. Magnesium is added to Zn-Al alloys in the amount of 0.03–0.08% with the aim to reduce the unfavourable effect of contamination and, especially PB and Sn, and by this, to limit the intercrystalline corrosion. Magnesium has also the influence on inhibition of structural transformations, affects insignificantly the increase of the tensile strength and, simultaneously, decreases elongation. In the case of magnesium contents higher than 0.06%, the endurance qualities of ZnAl and ZnAlCy alloys are distinctly lower; the content of higher than 0.1% deteriorates castability, increases brittleness at hot and leads to cracking in the casts. Similarly as magnesium, titanium affects in a similar way and their respective additives may inhibit structural transformations and ageing processes. Iron in cast alloys of zinc should not exceed 0.03%. The higher iron content affects the deterioration of mechanical properties and machinability and the decrease of resistance to corrosion. Nickel in the quantity of 0.02–0.03%, as added to copper-free zinc alloy is favourable for improvement of mechanical properties and increase of resistance to corrosion in hot water and in vapour.

It is worth to be mentioned that the composition of the alloy additives and their quantities are adjusted according to the specified conditions and the intended properties of a final zinc alloy. It is important to carry out the studies and tests as to find the optimal combination of alloy additives which will meet the expected, specified performance and quality requirements.

Standardized zinc alloys

The obligatory standard in the discussed respect is standard PN-EN 1774: “Zinc and zinc alloys. Cast alloys. Ingots and liquid metal” and PN-EN 12844: 2001 – “Zinc and zinc alloys. Casts. Specifications”. It is followed from the mentioned above documents that the most frequently applied alloy additive are aluminium and copper; however, there are also employed alloys, containing a small quantity of titanium (Tab. 1). The mentioned additives result in the change of mechanical properties but also, density or change in the range of melting temperature (Tab. 2).

Table 1. Chemical composition of casts from zinc alloys [1]

Signature of Zn alloy	Al	Cu	Mg	Ti	Zn
ZnAl4	3.7–4.3	0.1 max	0.025–0.06	–	Re
ZnAl4Cu1	3.7–4.3	0.7–1.2	0.025–0.06	–	Re
ZnAl4Cu3	3.7–4.3	2.7–3.3	0.025–0.06	–	Re
ZnAl8Cu1	8.0–8.8	0.8–1.3	0.015–0.03	–	Re
ZnAl11Cu1	10.5–11.5	0.5–1.2	0.015–0.03	–	Re
ZnAl27Cu2	25.0–28.0	2.0–2.5	0.010–0.02	–	Re
ZnCu1Ti	0.01–0.04	1.0–1.5	0.02 max	0.15–0.25	Re

Table 2. Properties of pressure casts from zinc alloy at temperature of 20°C (mean values, exclusively for the indicative purposes

Signature of Zn alloy	ZnAl4	ZnAl4Cu1	ZnAl4Cu3	ZnAl8Cu1	ZnAl11Cu1	ZnAl27Cu2	ZnCu1Ti
Tensile strength R_m. MPa	280	330	355	370	400	425	220
Total Elongation A_5, %	10	5	5	8	5	2.5	–
Brinell Hardness	97	114	130	95–110	95–115	105–125	–
Density, kg/cm³	6.7	6.7	6.8	6.3	6	5	7.2
Melting point range, °C	382–387	379–388	379–389	375–404	377–432	377–484	410–420

When comparing the data contained in Tab.1 and 2, it should be stated that ZnAl4Cu3 and ZnAl27Cu2 alloys demonstrated the highest hardness. It results from a high content of copper in the mentioned alloys (Tab. 2). However, due to a high content of aluminium in ZnAl27Cu2, the discussed alloy may be cast only in cold-chamber machines. Therefore, only the alloy with the chemical composition similar to that of ZnAl4Cu3 was considered in further tests aimed at the increase of strength properties. On the grounds of literature data [3–6], the addition of titanium at the level of 0.5% to ZnAl4Cu3 alloy was suggested.

The methodology of the studies

Casting and chemical composition of the test alloy

The studies on the possibility of alloying zinc with titanium were carried out in the industrial conditions, with the application of the industrial-scale demonstration line, consisting of two basic devices: induction furnace with overflow pump and hot-chamber high-pressure alloying machine Frech 125. Due to a similarity of construction of the structure of high-aluminium Zn alloys and the alloys based on Al (the presence of phase α in the both groups of alloys), the same mortars as for Al alloys were principally used for modification of alloys of zinc and aluminium. They include modifiers on the basis of Al which, however, require a considerable overheating of alloy what is unfavourable for its properties, and the application of immersing device in order to spread the mortar in metal bath. The mortars made on the basis of Zn e.g. ZnTi or ZnCuTi are deprived of the mentioned defects. The developed procedure of preparing the alloy is given below (Tab. 3). The new alloy has been called ZAMSINT.

Monitoring of chemical composition occurred during the whole process of alloy preparation. The cast was targeted at obtaining the chemical composition, amounting, respectively, to: 4% by weight Al, 3% by weight Cu and 0.2% by weight Ti. The analysis of the samples collected from the furnace of casting machine was carried out, directly after alloying as well as after separation of casting alloy at the period of ca. 16h (the alloy was hold in the preheating furnace until the next day) (Tab. 4).

The tests of the macrostructure of the samples, collected from the experimental products

The conducted experimental casts of zinc alloy ZnAl4Cu3 with different content of Ti were subjected to evaluation of macrostructure under microscope OLYMPUS SZX9. The exemplified macrostructures of ingot and die casting with the addition of Ti is given in Fig. 1 and 2. The die casting was performed from ZnAl4Cu3 alloy with the addition of Ti. We may observe a considerable effect of disintegrating impact of titanium.

Table 3. The procedure of preparing alloy of ZnAl4Cu3 with titanium

No.	Procedure of alloying:
1.	Load the induction oven with the first batch of ZnAl4Cu3 alloy (ingot)
2.	After melting the first batch of alloy, add the second part of ZnAl4Cu3 alloy
3.	Add AlCu mortar
4.	Wait for the complete melting at the full power of induction furnace (melting time ca. 1h:20min) temperature of the oven should amount to 440°C–450°C
5.	Add ZnTi2 mortar
6.	Check whether AlCu mortar has been dissolved (the mortar is lighter than ZnAl4Cu3 alloy and as being in a solid state, it flows out on the surface of the melted material)
7.	In the case of the incomplete dissolving of the mortar, wait for 15 minutes and again check the surface of the alloy in aspect of the presence of unsolved pieces of AlCu
8.	Transport the alloy to the oven of cast machine, using the pump, installed on the induction furnace

Table 4. Description of the samples, collected from the furnace, together with the measurement of their chemical composition

Description	Al	Cu	Ti	Mg	Fe	Zn
Chemical composition of the test alloy after alloying	4.45	3.15	0.558	0.035	0.0056	Re
Chemical composition of the test alloy after 16 h from alloying	4.12	2.98	0.35	0.035	0.0064	Re

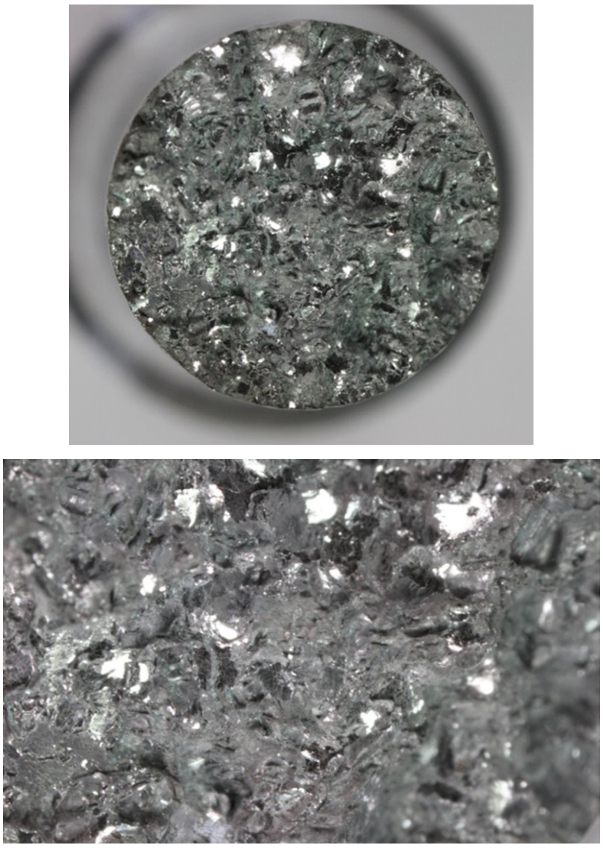


Fig. 1. Macrostructure of ingot

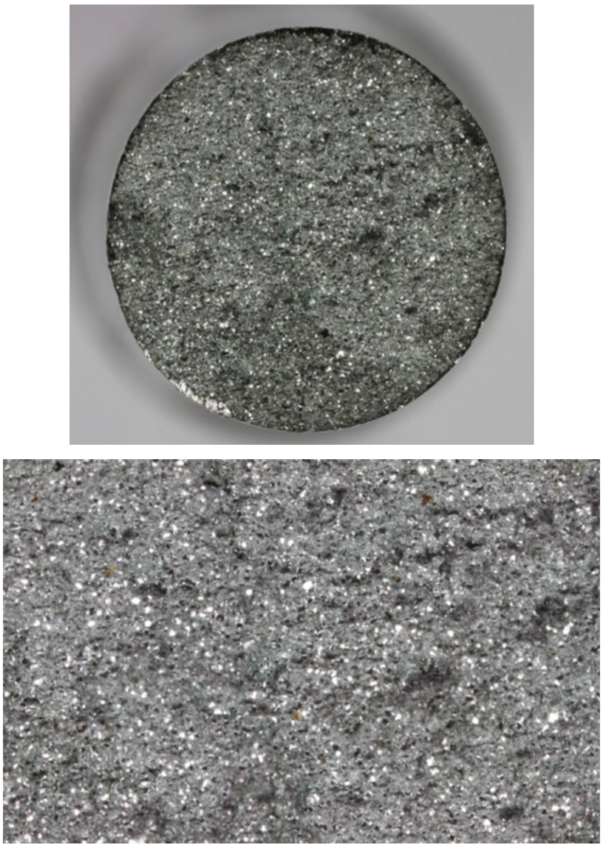


Fig. 2. Macrostructure of die casting from ZnAl4Cu3 alloy, modified with Ti

Testing of mechanical properties

The details, cast in the suggested technology, were subjected to a series of mechanical tests. At first, the tests with the samples cast in semi-industrial conditions to steel ingot mould were carried out. The alloy was prepared in resistance furnace, with mechanical agitation. In order to dissolve AlCu mortar, the overheating of the alloy up to 550°C was employed. Final content of titanium in the alloy was equal to 0.5% by weight. The endurance of the die-cast alloy, tested in the cylindrical samples performed according to PN was 265 MPa and the plasticity limit – 250 MPa. High-pressure casting is, however, characterized by significantly different conditions of the alloy's crystallization what gives, in effect, completely different mechanical parameters of the finished detail. Moreover, the casts made in the discussed technology are usually thin-walled what is favourable for better removal of heat, quicker crystallization and, in effect, disintegration of the alloy's microstructure. We should, therefore, expect considerably better strength parameters. The resulting cast has a complex shape, possessing the walls with a different thickness in its cross-section. As it is followed from the porosity tests, it is mainly perceived in the central part of material. The additional problem during the tests concerned a small dimension of the discussed detail, giving a small freedom to preparing the sample to the mechanical tests. Within the frames of the existing possibilities, the method for cutting out the samples for tensile strength tests was suggested (Fig. 3). The mentioned tests were carried out at the ambient temperature (Fig. 4). All tests were conducted with the test ZnAl4Cu3 alloy with titanium content amounting to 0.2% by weight. The discussed tests were implemented with the samples, collected from the stabilised part of the casting process, i.e. after thirtieth injection.

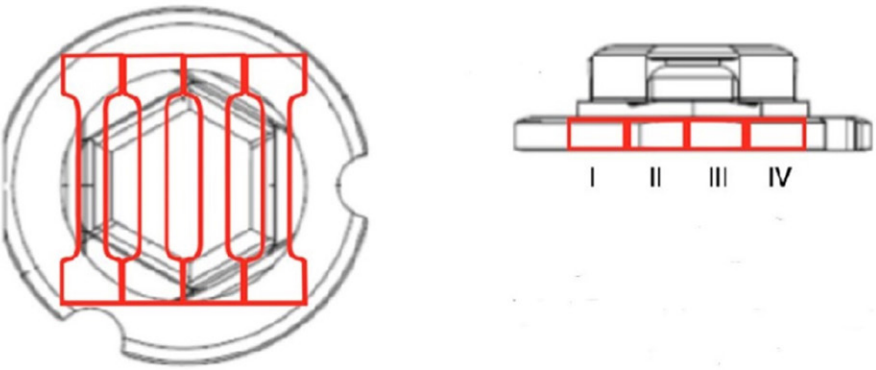


Fig. 3. A scheme of cutting out the samples for mechanical tests

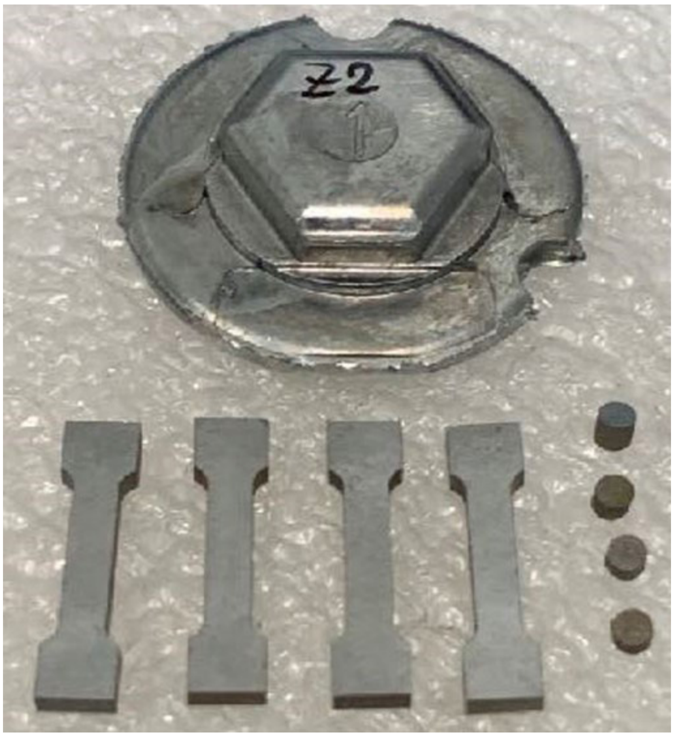


Fig. 4. Photos of the samples cut out for mechanical tests

The results of the tensile strength tests are given in Fig. 5, illustrating the strain-stress curves for the samples cut out from the casts. A strong correlation of the results is visible and the mean values presented in the table indicate that the tested material had a better strength than the material cast by gravitation. The differences in the elongation values may indicate the presence of micro-porosity in the middle part of the cast which was also present in the strength-tested samples. The mean hardness of material in this state was equal to 110HB.

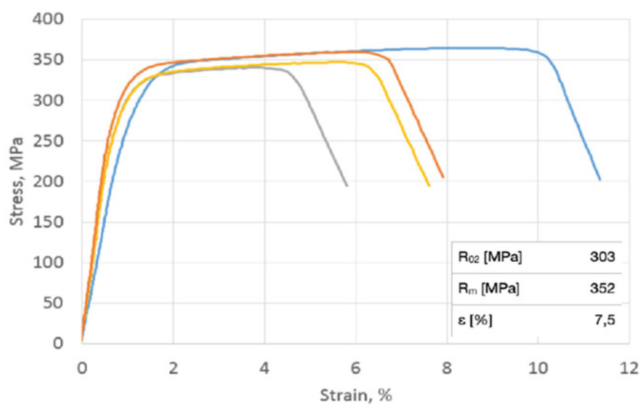
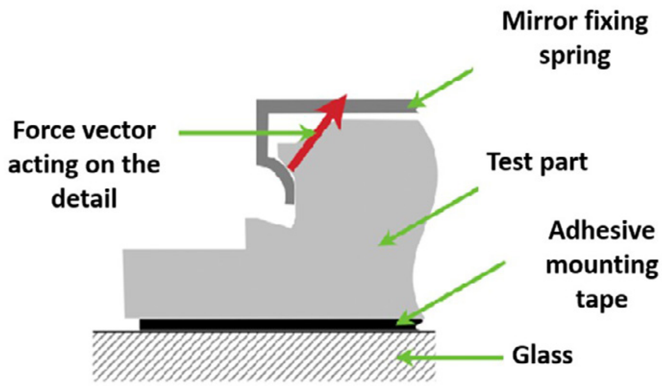


Fig. 5. Summary of the tensile strength tests for the samples from the research casts

Loads affecting the assembling detail of mirror

The measured mechanical parameters are the basis for confirmation of the alloy's suitability when applied to the loaded constructional elements. Apart from the material parameters, the correct analysis must consider the distribution of forces in the functioning detail. Due to its complex shape and complex scheme of strains for determination of maximum strains, the finite element method in respect of elastic strains, has been employed. To this end, the simulation package, as contained in SolidWorks software, has been utilized. For the needs of simulation, the simplified model; the forces affecting the detail were applied in parallel to the surface of "wings", transferring the load. The mentioned model together with the results of stimulation in a form of distribution of the equivalent (reduced) stress is given in Fig. 6.



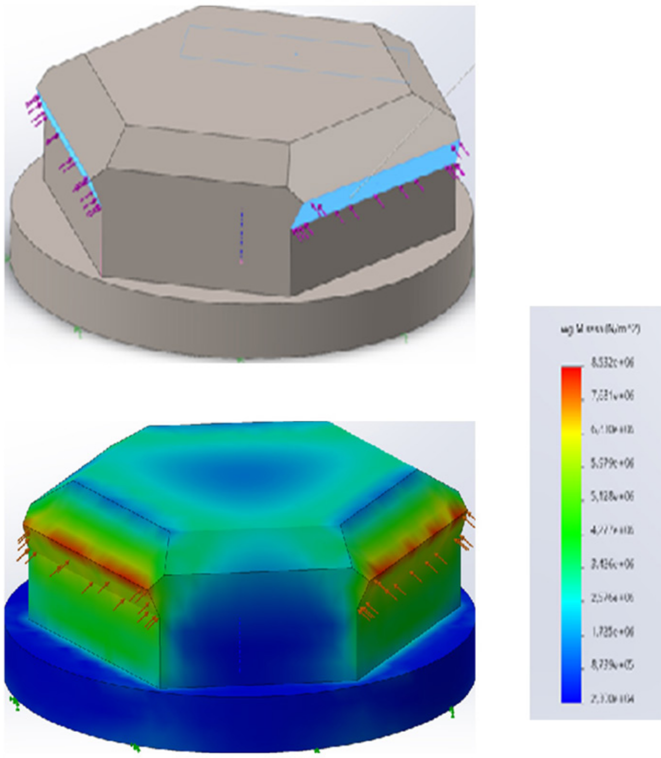


Fig. 6. Images of simulation of load, conducted in a model of detail, at the loading of the element with 30 kg weight

For the purpose of simulation, the force of 100N was applied; it was evenly distributed on the working surface of each of the 'wings' what corresponds to theoretical load of the detail with the element with 30 kg weight. The maximum calculated reduced stress amounted to 8.5 MPA, the analysis should be however extended to the situation of the mot unfavourable case of loading, i.e. when only one "wing" transfers the whole force (e.g. during bending of the mirror, fixed in the handle). In such situation, the application of the force corresponding to 100 kg load will increase the maximum stress in detail to value of 85 MPa. The calculated stress is still more than twice higher than the recorded one in tensile strength test at temperature of 100°C. It should be stressed that the above discussed calculations refer to extremely unfavourable loading conditions (in fact, the mirror fixing spring will give up at twice lower loads). The scheme of stress acting in detail is also more similar to compression or shear, so the comparison with the tensile strength test is an underestimation of the possibility of transferring the load by the mounting element. Summing up, the element cast from ZnAl4Cu3 alloy, being alloyed with Ti meets the safety requirements in aspect of the transferred static loads. The mentioned calculations have been confirmed in the presented below tests of loading of details with a constant force at the increased temperatures. Summing up, the static mechanical parameters of the examined components are considerably better than the previously presented mechanical parameters, obtained in the tests in ZnAl4Cu3 alloy with Ti, cast by gravitation, and they are fully sufficient for assurance of safe use of mounting element.

We should, however, mention that zinc alloys, possessing a relative low melting temperature as compared to other metallic constructional materials, may demonstrate unfavourable phenomena during loading in respect of alloy creep and high-cycle fatigue. Due to this reason, there were prepared and conducted the tests, considering the mentioned above phenomena in the context of fatigue work.

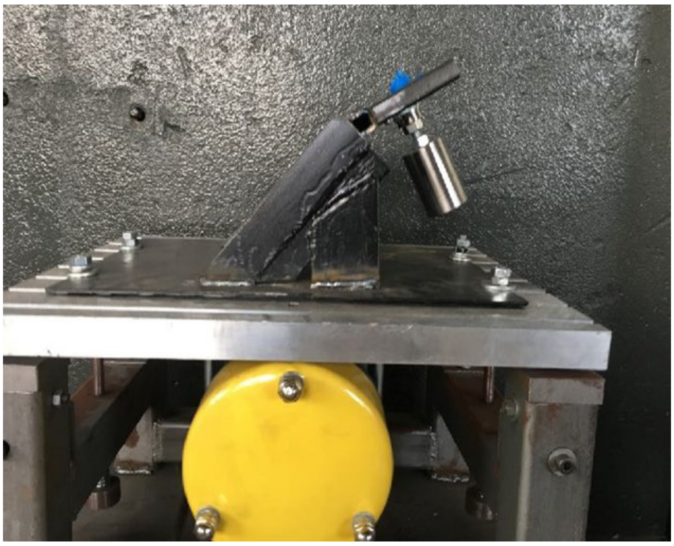


Fig. 7. Photo of a stand for fatigue tests with the assumed dedicated handle (grip)

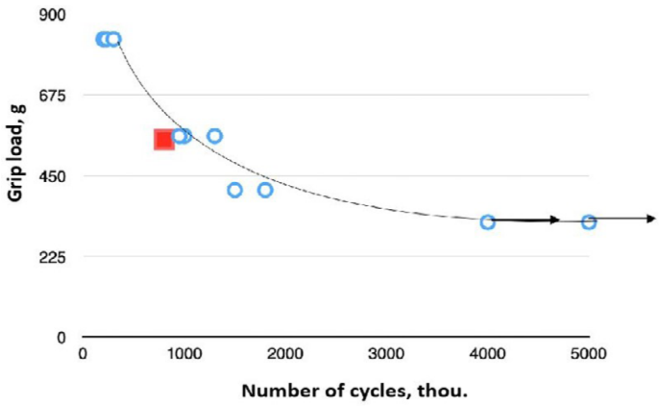


Fig. 8. Technological fatigue curve, representing the strength of detail, made from the tested ZnAl4Cu3 alloy with Ti, according to the number of cycles and load

Fatigue tests

The industrial fatigue tests were carried out on the produced details made from ZnAl4Cu3 alloy, alloyed with Ti and cast by high pressure technology. The mounting part decides on the endurance (strength) of the total element, transferring the load by the dedicated steel spring on the construction of the mirror. The element transferring the load is only a small part of the total detail what precludes making a sample for standardized fatigue tests. Due to this reason, we decided to conduct the industrial tests under the conditions, reflecting the work of the total assembly: glass-mounting handle-mirror. To this end, there was designed and performed a dedicated stand for the tests (Fig. 7). Its basis is created by vibration table, equipped with vibration motor, with an adjusted position of eccentric mass and frequency of work. The tested detail was fixed to glass background, equipped with the mounting system used in motor industry, utilizing a dedicated double-side tape by 3M company. The prepared set was mounted in the frame, screwed to T-table with construction enabling its positioning at the angle of 30 angular degrees what reflects the work under the operating conditions of car. All fatigue tests were carried out at a room temperature with frequency of 50 Hz and the recorded amplitude of vibrations (at the mirror), amounting to 1.5 mm. The fatigue destruction in the test with the application of original mirror, having a weight of ca. 550 g occurred after 800 thousand cycles and the cracking had place in the spring assembling part of the mirror and the tested detail remained intact. The discussed result is the evidence that the steel spring of the mirror is the most strained part of the total mounting set.

In further tests, the mirror was replaced with dedicated handles made from tool steel. The load was shifted in relation to mounting part so as to obtain the centre of gravity of the system analogical to that of real mirror. The tests were carried out for different loads and their result in a graphical form, analogical to Wohler curve is given in Fig. 8. If we adopt the fatigue strength of original mirror as equal to 800 thousand cycles with the assumed boundary conditions of vibrations, the cast details from ZnAlCu3 alloy, alloyed with Ti are found in the range, ensuring the safety of use.

Summing up

Within the frames of the implemented research-developmental work, the standardised ZnAl4Cu3 alloy was modified by addition of a new alloy component: titanium. It received the name: ZAMSINT. The developed innovative method of alloying in the induction furnace determines the maximum content of titanium addition at the level of 0.5%. There were also conducted the cast tests by gravitation method and with the application of high-pressure hot-chamber machine. The obtained components were controlled with the employment of the macroscopic tests, tensile strength tests, computer simulation of the strain and dedicated fatigue tests. All above mentioned operations have confirmed the correct properties of the alloy in relation to the basic material. The fatigue tests, as performed at the stand, simulating the real conditions of work have revealed the possibility of safe utilization of the set, consisting of the component made from ZAMSINT alloy at the level of 800 thousand cycles, satisfying the safety requirements of the discussed elements.

Literature

[1] PN-EN 12844: 2001
[2] Engineering in Zinc, Today's Answer, www.zinc.org
[3] Sailin Fan, Changjun Wu, Ya Liu, Hao Tu, Xuping Su, Jianhua Wang: 600 and 450°C isothermal sections of the Zn-Ce-Ti system. Journal of Alloys and Compounds 709 (2017) 842-849
[4] G. Piwowarski, J. Buraś, W.K. Krajewski: Wpływ zabiegu modyfikowania zaprawą ZnTi3,2 na mikrostrukturę stopu ZnAl10. Archives of Foundry Engineering Volume 13 , Special Issue 3/2013
[5] Wang Jianhua, Wang Xiande, Tu Hao, Su Xuping: Effects of titanium on microstructure and mechanical properties of ZZnal4Y alloy.
[6] Krajewski W.: Phases of heterogeneous nucleation in the ZnAl25 alloy modified by ZnTi and AlTi master alloys. Materials Research and Advanced Techniques 1996, 87(8): 645651.
[7] Walter Leis, Lothar Kallien, Ageing and creep behaviour of Zinc--Diecasting-Alloys, International Zinc Diecasting Conference "Tradition&Innovation", Prague, 2013
[8] Ageing of Zink Alloys, Lothar H. Kallien and Walter Leis, Aalen, Germany, International Foundry Research 2 64 (2011) No. 1.

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BIODEGRADABLE POLYMERS: POLYLACTIDE – PROCESSING, MECHANICAL PROPERTIES

POLIMERY BIODEGRADOWALNE: POLILAKTYD – PRZETWÓRSTWO, WŁAŚCIWOŚCI MECHANICZNE

Summary*: In the paper, a short review of literature concerning obtaining of polylactide (PLA, Polylactic Acid) and its properties was presented. The process of degradation was discussed. In the experimental part, the process of injection was carried out and the evaluation of mechanical properties based on the static stretching and impact strength tests was performed. The obtained results confirm that PLA may be processed in standard machines, without the necessity of their modifying. Values of stretching resistance, elongation at break (after fracture) and impact strength do not deviate from the typical parameters of plastics intended, for example, for packaging.*

Keywords*: polylactide, processing, mechanical properties*

Streszczenie*: W artykule przedstawiono krótki przegląd literatury dotyczący otrzymywania profilaktyku (PLA) i jego właściwości. Omówiono proces degradacji. W części doświadczalnej przeprowadzono proces wtrysku oraz dokonano oceny właściwości mechanicznych na podstawie próby statycznego rozciągania i udarności. Uzyskane wyniki potwierdzają, że PLA może być przetwarzany na standardowych maszynach, bez konieczności ich modyfikacji. Wartości wytrzymałości na rozciąganie, wydłużenia przy zerwaniu oraz udarności nie odbiegają od parametrów typowych tworzyw przeznaczonych na przykład na opakowania.*

Słowa kluczowe*: polilaktyd, przetwórstwo, właściwości mechaniczne*

Introduction

Together with the development of plastics industry over the world, the enormous manufacture of plastic products has been commenced [1, 2]. The mentioned industry has become a synonym of technical and economic progress. Plastics processing is simple and generates low costs in the case of mass and high-volume production as compared to other groups of materials. Plastics (polymers) are macromolecular compounds which may be obtained from synthetic or natural polymers. Materials produced from chemical compounds have a main defect – they are not subjected to biological degradation and become rubbish to natural environment [3].

The application of plastics in the world production is very wide. Practically, in each sector of economy, there are produced smaller or greater elements made from polymer materials. The increase of the waste increases the degree of natural environment burden what affects negatively the living conditions of plants, animals and humans. To mitigate the negative effects of this impact, the studies on the methods of obtaining and producing the polymers derived from the so-called "green chemistry", i.e. from renewable resources and the biodegradable ones, have been carried out [4–7]. In spite of a small percentage participation of biodegradable plastics in production, we may note its increasing level year by year. Additionally, the awareness of the consumers in respect of the correct waste selection is important. The care of the natural environment becomes not only a duty but also a trend in the contemporary world [8–11].

The biodegradation itself is the process where the decomposition of polymer material as affected by environmental factors has place [12]. The process is facilitated by the appropriate humidity and temperature of the environment and living organisms such as yeasts, bacteria and fungi which are present in the vicinity of the material. Polymer material may be subjected to the total degradation with the release e.g. of carbon dioxide, ammonia, methane or water, or only to a partial degradation e.g. of one component of the discussed material [11, 13]. The biodegradability of synthetic polymers is determined by their chemical structure [14, 15]. On the other hand, the rate of the biodegradability is affected, apart from humidity and heat, by the shape of the object, its geometry and thickness, etc. [16, 17]. Small crystallinity, a low molecular weight, chemical groups sensitive to effect of certain enzymes are favourable for biodegradation of polymers. The aliphatic polyesters meet the mentioned above requirements [8, 11].

The main branch of the application of biodegradable bioplastics includes packaging; the time of "life" (use) of a simple shopping bag is short and due to this, it is quickly discarded. PLA is more and more frequently used in packaging. It is a thermoplastic polymer material which becomes completely degraded during the period of half-a-year up to two years [8, 18]. Its good processing properties allow moulding by the basic methods such as injection, extrusion, extrusion with blowing and thermomoulding [19].

The aim of the present work is to make a general review concerning production, properties and processing of polylactide and presentation of the results of tests of the mechanical properties obtained in the samples performed during the process of bioplastics injection.

Polylactide (PLA)

PLA is a thermoplastic polymer which is easily formed. It is rigid, brittle, and has good barrier properties. PLA is bio-compliant; therefore, it is often used in medicine. PLA is characterized by a low degree of combustibility and it does not emit a smoke during the mentioned process. It is resistant to UV radiation, and is transparent [20, 21].

Manufacture

PLA may be obtained in many ways. As obtained by different methods, it has a different molecular weight and different properties in each of them. One of the methods of obtaining polylactide is the process of poly-condensation of lactic acid. It may be also produced by the chemical and biological synthesis. The second mentioned method is more preferred due to obtaining lactic acid from anaerobic fermentation of renewable resources such as glucose, maltose from potato or maize starch, saccharose from sugar cane of sugar beetroots and lactose from whey derived from milk processing [6, 22]. To obtain PLA with a high molecular weight, the reaction of polymerisation of lactide cyclic ring opening (*Ring Opening Polymerization,* ROP) is mainly carried out. During the mentioned reaction, we obtain PLA with a high molecular weight and good mechanical properties. The mentioned reaction runs in two stages [6, 11].

The first stage includes obtaining of lactide in reaction of depolymerisation from oligomers of lactic acid. The mentioned reaction is carried out under a lowered pressure, increased temperature and with the participation of catalysers [11].

During the second stage, the opening of the ring has place at the presence of catalyser. The mechanism of the discussed polymerisation may be cationic, anionic, coordinative or radical [6, 11].

The run of the reaction of poly-condensation and opening of lactide cycling ring is presented in Fig. 1 [11].

The degree of PLA crystallinity may be very high, even up to 60%. The temperature of melting is ca. 170°C–180°C, glass transition temperature is about 65°C. Crystallization occurs most quickly at temperature of 110°C. PLA is a thick plastic (1.2 – 1.3 g/cm^3). The resistance to stretching of PLA is not changed together with the increase of its molecular weight and is equal to ca. 60MPa [6, 10].

PLA has a high flavour (smell and taste) barrier and is resistant to the effect of fats. It reveals a capability of preserving the shape given during the production, for example, of film. Depending on the type of manufacture, molecular weight varies from 100 000 to 300 000.

The defect of PLA includes its water absorption. The lower is the degree of its crystallinity, the higher is the mentioned above capacity. It has a high polarity which makes a good adhesion to polyolefins in the multilayer structure impossible. It is soluble in organic solvents e.g. in petrol [8, 12].

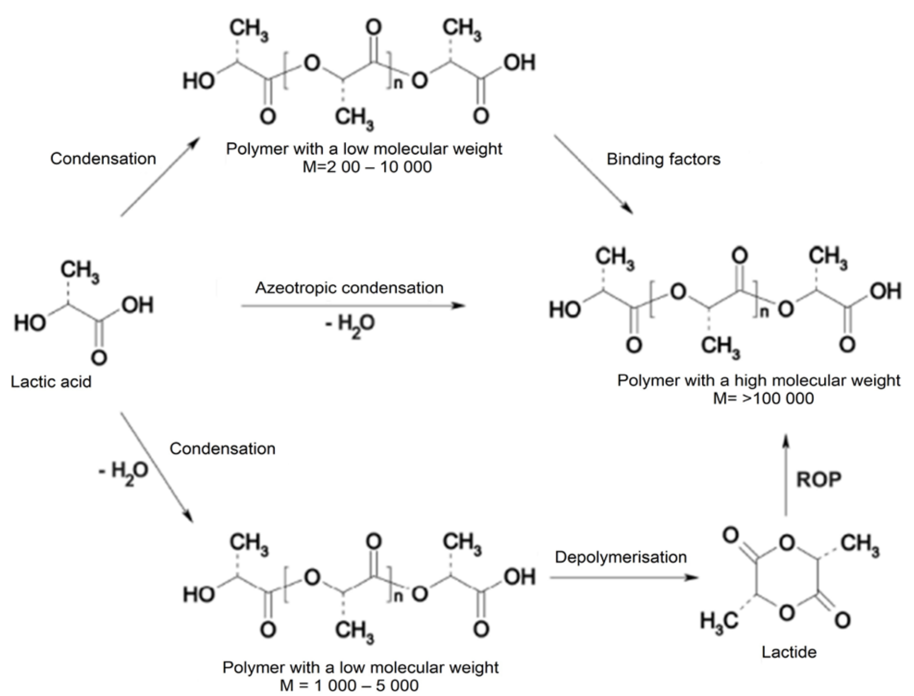

Fig. 1. The run of the process of obtaining PLA [11]

Biodegradation of PLA

Biodegradation of PLA in natural environment is dependent on many factors. From analysis of literature it is followed that the higher is the degree of crystallinity, molecular weight and the higher temperature of PLA melting, its degradation runs slower [23].

Hydrolytic and microbiological degradation

Biodegradation of PLA runs mainly in the environment with a high humidity and is divided into two stages [24]. During the first stage, the hydrolytic degradation occurs; water from the environment penetrates into the depth of the material, into its structure and it leads to hydrolysis of ester bonds in amorphous phase of PLA. As a result of such water activity, the shorter polymer chains are generated. Water-soluble oligomers penetrate the surrounding environment. In the case of a higher rate of the oligomers' release, as compared to the speed of water diffusion inside the material, we speak about surface erosion. When the rate of water penetration dominates over the speed of the release of oligomers, the erosion occurs in the total volume. In the successive stage, water-soluble mers and oligomers are metabolized by microorganisms, present in the environment to carbon dioxide, methane and water [3–12].

Biodegradation of PLA may run according to the existing conditions: slower or quicker. At the high temperature and at a high humidity of the environment, surrounding the material, the discussed process occurs relatively quickly. It is important that the rate of PLA degradation is equalized by the rate of assimilation of the products of its degradation by microorganisms. It was observed that most of the PLA-degrading microorganisms are capable of its degradation into carbon dioxide and water, and this, by turn, prevents accumulation of oligomers in the environment. Microorganisms capable of degrading microbiological and synthetic aliphatic polyesters, including PLA, were isolated from different soil environments [5, 24]. The population of microorganisms capable of degradation of PBH and PCL occurred to be most numerous; the lowest one was that of capable of PLA degradation. The tests, comparing the rate of degradation of the mentioned polyesters in the soil revealed that PLA was least sensitive to microbiological attack. To commence the process of PLA degradation, a long period is necessary; later, it runs also very slowly [24].

Under the composting conditions where the temperature is found at the level of 50-60°C and humidity is equal almost to 100%, the degradation of PLA into monomers and oligomers runs for 45-60 days. On the grounds of literature studies, it was stated that the greatest decrease of the molecular weight and a distinct PLA degradation occurred in the conditions of industrial composting. The industrial compost means creation of a special environment, the content of which includes a specified composition of biological material e.g.: 40% of leaves, 30% of wood chips and ca. 30% grasses. The process of PLA products' composting is carried out at the depth of one meter. In the case of degradation of the same samples in a normal soil is very slow [1–24].

PLA application

Due to its thermal flexibility and the possibilities of processing in typical equipment and good mechanical properties, biodegradability, non-toxicity of the material itself as well as the products of its decomposition, PLA finds a very wide application in medicine. It is employed as biodegradable plastic in production of bioresorbable surgical threads, clips, staples, surgical nets as well as screws for osteosynthesis of fractured bones and the capsules, releasing the assumed dose of medicine at the assumed time. The products, made from PLA include also membranes, which accelerate healing of the extensive wounds, sanitary agents, surgical masks and medical protective clothes [25–36].

Another application includes packaging such as bands, labels, bags for wastes, bottles for drinks and food packaging. It is perceived as the main direction of the future PLA application [11, 17].

In agriculture, the discussed material is used as protective films in plant cultivation, and for the tunnels that protect flowers, vegetables and also young trees against the effects of pests and negative temperatures. After termination of the utilization period, the mentioned products remain in the soil and are subjected to biodegradation, additionally enriching it [11].

Moreover, PLA is used as a feedstock material in 3D printers in a form of threads with ea specified diameter, being called filaments. It is one of the basic materials, employed in 3D printers, working in the additive manufacture technology FDM (*Fused Deposition Modelling*). It is characterized by a high simplicity of printing and strength properties appropriate for most of prototype elements, especially those decorative ones. PLA is available in a very wide spectrum of colours. The discussed material is not resistant to long-lasting effect of increased temperatures, above 60°C and after a certain time, it becomes irreversibly deformed. PLA is not suitable for printing of elements, working long time under the pressure. It is anticipated that the range of PLA applications will become systematically increasing [33–36].

Material and methods of the studies

In the studies on the evaluation of the possibility of PLA processing, the material of Nature Works company, type Ingeo Biopolymer 3251 D intended for processing in the injection technology, was employed.

In the preparation of the test samples, the screw injection moulding machine by Ponar Żywiec, series UT 90 for thermoplastic materials, was used. It is a horizontal screw injection machine; it has 5-score, double level system of closing a mould and a direct driving system of the screw with high-momentum hydraulic engine. The remaining laboratory equipment included: injection mould, electronic balance DARwag, dryer KC 100/200 and mill for grinding of plastics.

Before commencing the injection process, the initial material in a form of granulate, was dried in order to remove water. After drying, plastic was subjected to process of injecting the samples in order to evaluate mechanical properties. In Table 1, the parameters of the injection process have been given.

Endurance properties in the test of static tensile properties were conducted in accordance with standard PN-EN ISO 527-2:2012 Plastics –Part 2: Determination of tensile properties of plastics – test conditions for moulding and extrusion plastics.

Table 1. Parameters of injecting the polymer material (PLA)

Injection parameters	Values
Injection:	
Speed	20%
Pressure	80 bar
Alloy temperature	200°C
Pressing:	
Time	5s
Pressure of holding	40 bar
Force of closing	
Mean	887 N
Closing of mould:	
Pressure	175 bar
Speed	40 %
Time of mould protection	5 s
Time of cycle	90 s
Counter pressure	5 bar
Opening of mould:	
Counter pressure	10 bar
Time of cooling	15 s
Temperature of mould	20°C

The determination of impact strength was carried out by Charpy method, in pendulum hammer in conformity with standard PN-EN ISO 179-1:2010 Plastics – Charpy impact strength of plastics under defined condition. Part 1: Non-instrumented impact test.

The results and their discussion

Determination of the material strength and deformation were carried out in accordance with standard PN-EN ISO 527-2:2012. The measurement consisted in stretching, with a constant velocity, of standardized samples in a form of paddles, performed by injection technology in conformity with the respective obligatory standards in this respect. In Table 2, the obtained results of the tensile properties, elongation after fracture and impact strength of plastic have been presented.

The impact strength test was carried out by Charpy method in accordance with standard PN-EN ISO 179-1:2010. The mentioned method consists in placing a sample in a form of standardized beam on a special bed in the vicinity of its ends and it is hit with the hammer of a respective energy [1, 2]. In Table 2, the impact strength of the material has been presented.

Table 2. The results of the test of mechanical properties of plastics

Parameter	Result	Standard deviation
Mean tension, MPa	74,7	0.62
Mean deformation, %	11.0	0.08
Mean impact strength, kJ/m²	19.0	0.12

The obtained results of the basic mechanical properties do not deviate from those ones, found in literature. The employed material did not make any serious troubles during determination of the parameters of injection of test beams and paddles. During the tensile strength test, the material was showed a brittle cracking. Its behaviour was similar to that one of low-impact PS (polystyrene) what was also confirmed by the results obtained for impact strength test.

Summing up

Due to a fact of decreasing world oil resources and the need of protecting the natural environment, the search for the materials obtained from renewable resources and subjected to controlled biodegradation processes, becomes our target. Aliphatic polyesters belong to a group of the mentioned materials, where PLA is a subject of the intensive research and implementation work. The progress in technology of PLA manufacture causes that the discussed material becomes cheaper and by this, it drives out the traditional polymer materials from the market.

The subjected trials of processing and the results of the tests of mechanical properties of the discussed material have demonstrated that it may be successfully processed in typical processing machines without the necessity of their special modification.

Literature

[1] Wilczyński K. (red.), Garbarski J., Nastaj A., Lewandowski A., Fabijański M., Wilczyński K. J., Buziak K., Narowski P., Zawistowski H.: Przetwórstwo tworzyw polimerowych Oficyna Wydawnicza Politechniki Warszawskiej, 2018.

[2] Soroczyński, A., Haratym, R., Rechowicz, K.: Energy intensity as an ecological factor in the selection of the manufacturing process. Welding Technology Review, (2019). 91.

[3] Yottakot, S., Leelavatcharamas, V.: Isolation and Optimisation of Polylactic Acid (PLA)-packaging-degrading Actinomycete for PLA-packaging Degradation. Pertanika Journal of Tropical Agricultural Science (2019) 42 (3).

[4] Świerz-Motysia B., Jeziórska R., Szadkowska A., Piotrowska M.: Otrzymywanie i włąściowści biodegradowalnych mieszanin polilaktydu i termoplastycznej skrobi. Polimery 56.4 (2011), 271.

[5] Pawłowski Ł., Bartmański M., Zieliński A.: pH-dependent composite coatings for controlled drug delivery system – Review, Inżynieria Materiałowa 3 (229), (2019), 62÷67.

[6] Sin, L. T., & Tueen, B. S.: Polylactic acid: a practical guide for the processing, manufacturing, and applications of PLA. William Andrew (2019).
[7] Sen-lin Yang, Zhi-Hua Wu, Wei Yang, Ming-Bo Yang: Thermal and mechanical properties of chemical crosslinked polylactide (PLA), Polymer TestingVolume 27, Issue 8, (2008), 957–963.
[8] Fabijański, M.: Wytrzymałość mechaniczna oraz palność polilaktydu. Przemysł Chemiczny, 98, (2019), 556-558.
[9] Chmielewski, T., Hudycz, M., Krajewski, A., Sałaciński, T., Skowrońska, B., Świercz, R. (2019). Structure Investigation of Titanium Metallization Coating Deposited onto AlN Ceramics Substrate by Means of Friction Surfacing Process. Coatings, 9 (12), 845.
[10] P. Pawelzik, M. Carus, J. Hotchkiss, R. Narayan, S. Selke, M. Wellisch, M. Weiss, B. Wicke, M. K. Patel: Critical aspects in the life cycle assessment (LCA) of bio-based materials – Reviewing methodologies and deriving recommendations. Resources, Conservation and Recycling, Vol. 73 (2013) 211-228.
[11] Lima L.-T., Aurasb R., Rubinob M.: Processing technologies for poly(lactic acid), Progress in Polymer Science, 33, (2008), 820–852.
[12] Żenkiewicz, M., Richert, J.: Synteza, właściwości i zastosowanie polilaktydu. Przetwórstwo Tworzyw, 15 (5), (2009), 192-199.
[13] Fabijański M: Mechanical Properties of Polylactide Filled with Micronized Chalcedonite, Journal of composites science, 2022; 6 (12):387. https://doi.org/10.3390/jcs6120387
[14] Foltynowicz Z., Jakubiak P.: Poli(kwas mlekowy) – biodegradowalny polimer otrzymywany z surowców rooelinnych, Polimery, 47, 11 – 12, (2002), 769.
[15] Duda A.: Polilaktyd – tworzywo sztuczne XXI wieku?, Przem. Chem. 82, 8 – 9, (2003), 905.
[16] Fabijański M.:Effect of multiple processing on the strength properties of polylactide/polystyrene mixture, Przemysł Chemiczny, Volume 101, Issue 1, Page 65-68, 2022 DOI10.15199/62.2022.1.9
[17] Mathew AP., Oksman K., Sain M.: Mechanical properties of biodegradable composites from polylactic acid (PLA) and microcrystalline cellulose (MCC). J. Appl. Polym. Sci. 97, (2005), 2014–25.
[18] Drumright R. E., Gruber P. R., Henton D. E.: Polylactic acid technology. Adv. Mater. 12, (2000), 1841–1846.
[19] Janczak, K., Dąbrowska, G., Hrynkiewicz, K., Raszkowska-Kaczor, A.: Poszukiwanie grzybów zdolnych do wzrostu na tworzywach polimerowych. Przemysł Chemiczny, 93, (2014), 1206-1209.
[20] Malinowski, R., Łubkowski, D.: Badanie wpływu temperatury i czasu suszenia na wybrane właściwości polilaktydu (PLA). Inż. Aparat. Chem, 49 (5), (2010), 77-78.
[21] Nowak, W., Fabijanski, M.: Wpływ działania podwyższonej temperatury na wyroby z materiałów polimerowych. Opakowanie, 1, (2014), 55-58.
[22] Siwek, P., Libik, A., Twardowska-Shmidt, K., Ciechańska, D., Gryza, I.: Zastosowanie biopolimerów w rolnictwie. Polimery, 55 (11-12), (2010), 801-811.
[23] Fabijański, M.: Wielokrotne przetwórstwo polilaktydu. Przemysł Chemiczny, 95(4), (2016), 874-876.
[24] Kruk, A., Gadomska-Gajadhur, A., Ruśkowski, P: Zastosowanie bioresorbowalnych rusztowań w inżynierii tkankowej. Tygiel (2015), 91, 102.
[25] Malinowski, R., Żenkiewicz, M., Richert, J.: Wpływ wybranych czynników sieciujących na stopnie zżelowania i spęcznienia polilaktydu. Przemysł Chemiczny, 91, (2012), 1596-1597.
[26] Maślanka, S., Siołek, M., Hamryszak, Ł., Łopot, D.: Zastosowanie odpadów z przemysłu mleczarskiego do produkcji polimerów biodegradowalnych. Chemik, (2014), 68 (8).
[27] Gadomska-Gajadhur, A. A., Mierzejewska, J., Ruśkowski, P., Synoradzki, L.: Otrzymywanie sfer polilaktydowych zawierających paracetamol. Przemysł Chemiczny, 94 (10), (2015), 1676-1678.
[28] Pluta M.: Morphology and properties of polylactide modified by thermal treatment, filling with layered silicates and plasticization, Polymer 45, (2004), 8239.
[29] Fabijański, M., Garbarski, J.: Wpływ wielokrotnego przetwarzania na właściwości wytrzymałościowe mieszaniny polilaktyd/polipropylen. Przemysł Chemiczny, 96 (3), (2017), 567-570.
[30] Soroczyński, A.: Regeneration of Foundry and Core Masses. Journal of Manufacturing Technologies, 41(4), (2016), 29-33.
[31] Stasiek, A., Raszkowska-Kaczor, A., Janczak, K.: Spienianie polilaktydu. Przemysł Chemiczny, 93 (1), (2014), 117-119.
[32] Frydrych, J., Kaczmarczyk, M., Kaszuba, A., Mężykowska, A., Romanowska-Osuch, A., Bartkowiak, A.: Wpływ dodatku napełniaczy mineralnych oraz polimerów biodegradowalnych na wybrane właściwości polilaktydu. Przemysł Chemiczny, 96(2), (2017), 375-379.
[33] Fabijański, M.: Wpływ zawartości węglanu wapnia na właściwości mechaniczne polilaktydu. Przemysł Chemiczny, 96 (4), (2017), 894-896.
[34] Fabijański, M.: Właściwości mechaniczne kompozytów na osnowie polilaktydu napełnionych mączką drzewną. Przemysł Chemiczny, 98, (2019), 1246-1248.
[35] Żenkiewicz, M., Richert, J., Rytlewski, P., Richert, A.: Niektóre właściwości kompozytów polilaktydu z szungitem. Przemysł Chemiczny, 90, (2011), 631-635.
[36] Nofarab M., Sacligilb D., Carreauc P. J., Kamald M. R., Heuzeyc M-C.: Poly (lactic acid) blends: Processing, properties and applications, International Journal of Biological Macromolecules, 125, 15, (2019), 307-360.

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STRENGTHENING THE GEAR TEETH WITH SURFACE WORK

WZMOCNIENIE PRZEKŁADNI KÓŁ ZĘBATYCH OBRÓBKĄ POWIERZCHNIOWĄ

***Summary**: The present paper considers the beneficial effects that can be obtained by cold work type of machining performed as the final technological treatment in the process of gears manufacturing. Limitations in the use of shot blasting as a method of surface cold work of gears were pointed out and the concepts of two devices for carrying out the cold work with much greater efficiency than in the case of shot blasting were presented. The discussed devices use pressure burnishing of the critical zones of the gears.*

***Keywords**: cold machining, surface cold treatment, shot blasting, gear*

***Streszczenie**: W artykule rozważono korzystne efekty, jakie można uzyskać stosując obróbkę nagniataniem na zimno, wykonywaną jako końcowa obróbka technologiczna w procesie wytwarzania kół zębatych. Wskazano ograniczenia w stosowaniu śrutowania jako metody powierzchniowej obróbki na zimno przekładni oraz przedstawiono koncepcje dwóch urządzeń do prowadzenia obróbki na zimno ze znacznie większą wydajnością niż w przypadku śrutowania. Urządzenia te wykorzystują nagniatanie naporowe krytycznych stref zębów kół zębatych.*

***Słowa kluczowe**: obróbkę skrawaniem na zimno, powierzchniowa obróbka na zimno, śrutowanie, przekładnia*

Introduction

In many fields of drive technology, especially in mining, construction, road and agricultural machines and in vehicles, it is necessary to use mechanical gears to obtain high torque, often at moderate speeds. Gears with involute tooth profiles are most often used, which is mainly due to the ease of obtaining involute profiles using envelope methods.

The development of toothed gears has resulted in the development of many methods

to improve the operational properties of gears by design, material, selection of manufacturing technology and proper operation to increase both service life and safety [1, 2].

The basic processes that generate the wear and failures of the gears meshing, such as fatigue breakage of the teeth, abrasive and erosive wear, fatigue chipping of the surface layer of working surfaces of the teeth (pitting) and sometimes the phenomenon of tooth seizing, cause premature loss of the gear's usability, causing large technical and economic losses, and even resulting in an increased risk [3].

Technological treatments in the form of special types of heat treatment of gears made of steel, and especially thermo-chemical treatments, make it possible to achieve a significant improvement in resistance to the aforementioned destructive processes [6]. To a small extent, however, the additional large possibilities created by the use of cold work of the toothing of the gears are used [4].

Surface deformation as a method of improving the usable properties of gears

Cold work, i.e. operation below the recrystallization temperature of the material, has been known for a long time [4]. It was used to obtain favourable features, e.g. in the production of white weapons (swords), when the essence of the processes that then take place in the surface layer of the strengthened element was not yet known. Many technologies used in the practice of manufacturing elements from metal alloys, especially iron (Fe) alloys, have been developed to improve selected functional properties [4-6]. In the case of gears, shot preening is used, which consists in the action of a stream of, most often, steel balls falling at high speed on the treated surfaces. The kinetic energy of individual balls causes overlapping plastic deformations of the surface layer, which positively changes the usable properties. As a result of shot preening, the hardness of the strengthened surface layer increases, the surface roughness pattern changes, and, above all, residual compressive stresses are formed to a depth depending on the initial hardness of the work piece and the kinetic energy of the falling balls [4]. A jet of balls is ejected with compressed air or by rotor mechanical ejectors.

When machining elements with greater hardness, shot blasting encounters a number of technical limitations.

Pneumatic ball jet ejection has a physically limited airflow velocity through the jet nozzles. With the increase in the rotational speed of the mechanical rotor ejectors, the abrasive wear of the device elements increases strongly, and the fine-dispersion metallic dust formed at that time poses a danger of explosion [4].

Sometimes the use of carrier liquid for the stream of balls eliminates some of the aforementioned phenomena, but by wetting the surface of the strengthened elements, the contact pressure of the falling balls is limited, which must "breakthrough" the layer of liquid, which significantly reduces the efficiency of shot blasting.

In the case of shot preening of gear teeth, additional difficulties arise. The most stressed zones of the teeth at their base have definitely more difficult access of the ball stream due to the increased distance from the nozzle outlet, which results in a partial loss of kinetic energy of the stream. In addition, the transition radius zone at the base of the teeth cannot be crushed to the required depth.

In the described situation, the best way to generate deformation of a sufficiently large depth is pressure burnishing, which allows obtaining good strengthening effects at the full height of the teeth, with particular emphasis on the zone of the transition radius of the tooth outline. Reinforcement of the bottom of notches is of particular importance from the point of view of the tooth resistance to fatigue fracture. In this zone, the initiation and then the development of tooth fatigue cracks, the most critical form of operational damage to the gears, usually takes place [3].

Irrespective of the method of obtaining the surface deformation of orking zones of the teeth, the most important effect of this type of machining is the formation of a state characterized by constant internal stresses in the surface layer of the teeth of a compressive nature. These stresses in a very favourable way change the resultant state of variable stresses occurring during the operation of the gears. There is a reduction of the resultant stresses in the stretching zone, especially at the base of the teeth that is caused by the bending moment of the teeth. The summation of stresses on the compression side does not matter, because the compressive strength, especially fatigue strength, of the materials for gears is many times higher than the tensile strength due to the concave curvature.

The favourable compressive stresses generated by the surface work treatment, which balance the favourable compressive stresses, cause that the appropriate tensile stresses occur in the core of the material with a much larger load-bearing cross-section and in the section of the tooth cross-section where the bending stresses are lower. They are, therefore, of little importance for the resultant state of tooth material effort and do not affect the reduction of the service life of the gears. The increase in the hardness of the surface layer obtained in the process of deformation treatment serves improving the resistance to abrasive and erosive wear of the teeth. The transformation of retained austenite, which occurs as a result of heat treatment of steel wheels, is also beneficial. It is important to eliminate machining scratches that occur with typical methods of machining gears. The very unfavourable system of roughness's parallel to the axis of the gears as a result of cold work, regardless of the method, results in a more favourable non-directional character of the roughness, which has a beneficial effect on the incubation and development of tooth fatigue cracks. In the layer subjected to crushing in terms of microstructure, grain fragmentation is favourable and the dislocation density increases [8, 9]. The tribological properties of the working surface of the teeth are improved as a result of surface deformation treatment, because the adhesion of lubricants to the tooth surfaces treated in this way is improved. The relief of the tooth surface created as a result of machining, especially by shot preening, creates numerous "lubricating pockets" that facilitate the formation of a lubricating film. It also increases the resistance of the teeth to sudden overloads and scuffing.

Together, the described effects result in a significant increase in the service life of the gears after cold work.

The concept of devices used for surface cold work of gears by pressure burnishing

In the Department of Mechanization and Robotization of Mining at the Silesian University of Technology, a number of devices concepts for the implementation of strengthening of gears by surface work through pressure burnishing have been developed. In this way, the previously described numerous limitations that occur in shot blasting are eliminated, and the parameters of the treatment process can be easily adjusted within wide limits [12÷15].

A device for pressure burnishing of the transition radius zone at the base of the gear teeth

The transition zone at the base of the teeth is burnished using a universal device, the design of which is shown in Fig. 1.

The gear wheel 4 to be machined is mounted on the end of the piston rod 8 of the double-acting hydraulic cylinder 18. It is secured by a quick-release nut 21. The 6 transition radius zones of the workpiece gear are burnished simultaneously with burnishing rollers 2 loosely mounted on the axles 3. Pressing rollers are pressed against the gear being machined by marked disc springs 5. The amount of burnishing force is controlled by the position of the nut 6. The burnishing head holders 10 are fixed to the base of the device 11. It is advantageous to use three holders 10 evenly distributed around the circumference of the base at an angle close to 120°.

When the number of teeth of the burnished wheel 4 is divisible by three, the aforementioned angle of the housings distribution is exactly 120°. This configuration serves to fully balance the forces acting on the gear wheel being machined, eliminating the side forces acting on the piston rod 8. A single burnishing cycle

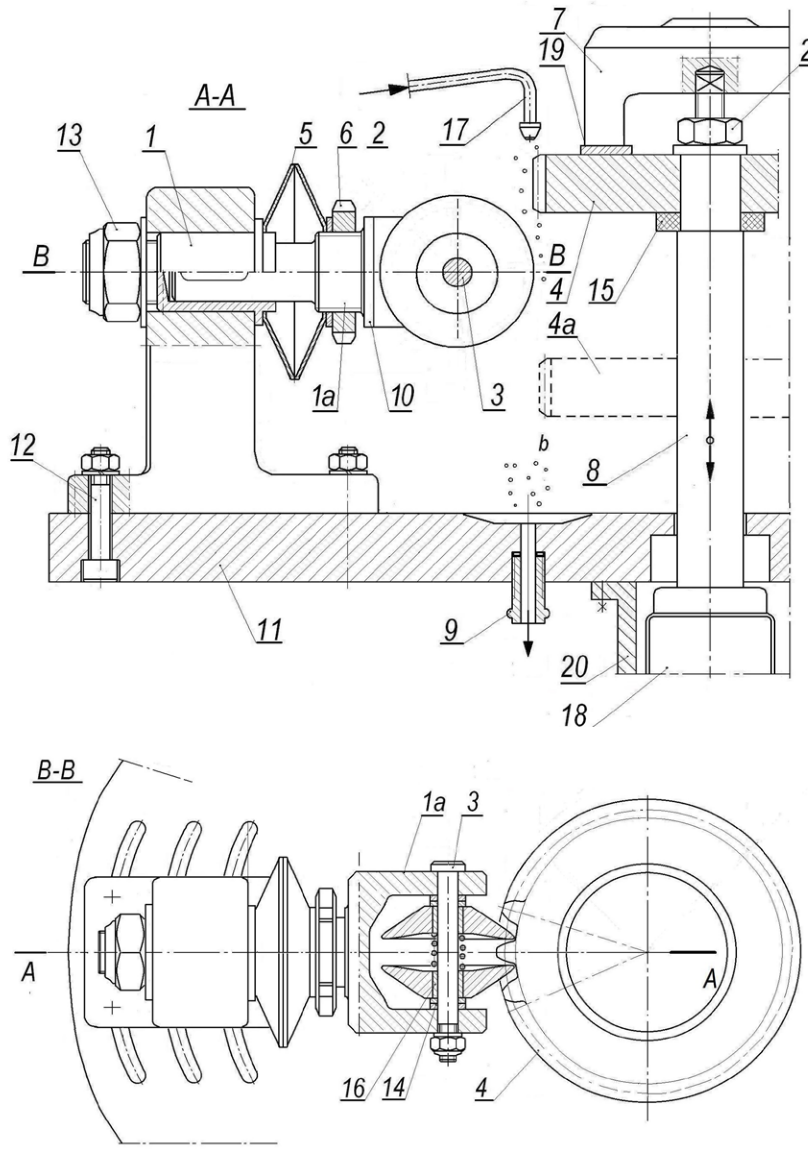

Fig. 1. Device for pressure burnishing of the bottom of gear grooves

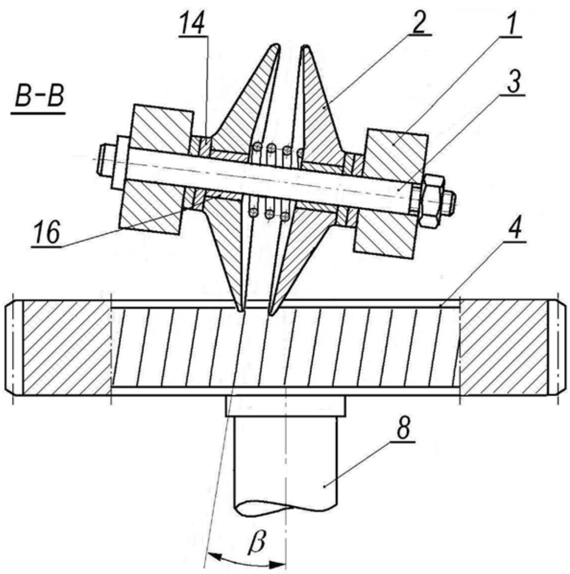

Fig. 2. Adaptation of the device from Fig. 1 for burnishing of helical gears

consists in moving the machined wheel in the up-down system from the initial position 4 to the final position 4a and back. During burnishing, the cooling and lubricating liquid is automatically sprayed through nozzles 17. This ensures high smoothness of the gear surface being machined and eliminates the occurrence of unfavourable phenomena of recrystallization of the burnished surface layer as a result of temperature increase.

After the simultaneous burnishing of six transition radii, the turntable 7 rotates the wheel 4 by the angular pitch of the teeth. It is advisable to repeat the burnishing procedure several times with possibly increasing pressure of the burnishing rollers 2. The burnishing rollers should be made of steel subjected to heat and chemical treatment to high hardness, and the roller radii should be polished. Alternatively, carbide rollers can be used.

When there is a need to machine gears with helical teeth, the burnishing heads should be turned by the angle β corresponding to the angle of the inclination of helical teeth (Fig. 2). During the burnishing of the oblique teeth, the machined wheel rotates automatically on the end of the piston rod 8.

As a result of pressure burnishing with the described device, a significant increase in the resistance of the teeth to fatigue breakage is achieved due to the formation of compressive residual stresses in the surface layer of the transition radius zone; it provides obtaining high surface smoothness and elimination of tooth machining scratches, too.

The burnishing device is characterized by great versatility. It enables the machining of gears with different number of teeth, corrected and non-corrected wheels, modified and unmodified teeth, and after replacing the burnishing rollers, it is possible to machine gears with a wide range of modules. It is also characterized by high treatment efficiency with low energy consumption.

The concept of devices used for surface cold work of gears by pressure burnishing

The basic tool of the device for the implementation of deformation treatment by burnishing the working surfaces of the gear teeth is a toothed wheel equipped with movable burnishing rollers. A single tooth of such a tool is shown in Fig. 3.

Burnishing rollers 2 are located on the whole tooth profile of the tool-wheel 1, held by covers 6 that are connected with bolts 4 and 5. Rolling rollers of needle roller bearings can be used as burnishing rollers after appropriate adaptation of their ends.

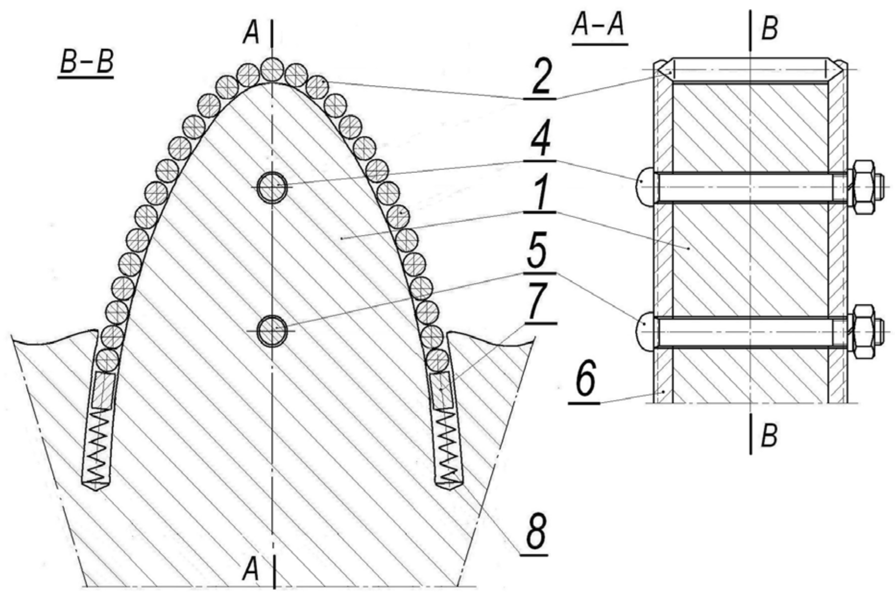

Fig. 3. Tool for pressure burnishing of working surfaces of gears

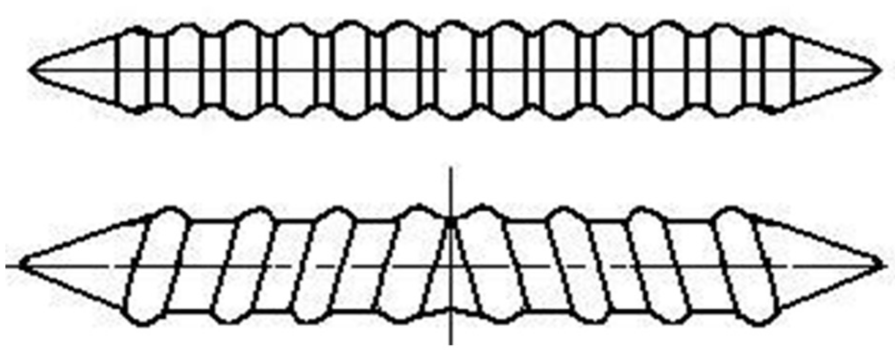

Fig. 4. Exemplary shapes of burnishing rollers with increased contact pressures for use in the burnishing tool from Fig. 3

a way as to increase the slip (actually rolling) during burnishing in the area of the tooth base. This serves to intensify the burnishing process in the more critical part of the tooth height.

Supporting the set of burnishing rollers 2 on beams 7 and springs 8 allows them to freely roll over the burnished tooth profiles and then return to the starting position.

During the burnishing procedure, an intensive spray of cooling and lubricating liquid should be used to eliminate unfavourable excessive heating of the elements. It is also possible to perform burnishing in full immersion in a cooling and lubricating liquid.

Depending on the needs, one-sided or double-sided tooth machining can be used, especially for gears operating in reversing systems or intermediate gears. When machining on two sides, the gear must be turned over to the other side. Also, the gear-tool is purposeful to be turned over periodically for even wear of the tool.

After appropriate adaptation of the device, it is possible to process helical gears and roof gears. Noteworthy is the low energy consumption and high efficiency of wheel machining. Gears made of various materials can be machined, with particular emphasis on wheels made of steel after thermal improvement and carburized wheels. However, machining of wheels after nitriding or nitrosulphurization should be avoided due to the possibility of exfoliation of the thin layer of tooth material strengthened by nitriding.

A water-oil emulsion commonly used for cooling during machining can be used as a cooling and lubricating liquid.

Burnishing rolls may have cylindrical working surfaces or have humps, as shown in Fig. 6. These humps are used to increase the contact pressures of the rollers when burnishing the working surface of the teeth of gear being machined. Forming rolls like 2a requires additional longitudinal feed during burnishing.

The spiral formation of burnishing humps as shown in pos. 2b can be make without of the longitudinal feed of tool or burnished gearl. The opposite shape of the spiral humps along the length of the burnishing rollers limits the generation of longitudinal forces during machining. The burnishing treatment consists in the cooperation of the wheel-tool with the machined gear under appropriately selected pressure. Additional braking of the machined gear is desirable.

The tooth profiles of the tool wheel should be made so that the envelope of the burnishing rollers corresponds to the involute profile of the teeth of the mating gear, intended to work in tandem with the currently burnished gear. The correction of the shift of the outline of the teeth of the wheel-tool can be selected in such

Final remarks

The selection of the optimal burnishing treatment parameters for both described devices can only be made by the trial method because of the huge number of gears sizes, their modules, types of materials, applied tooth treatment methods, parameters of heat treatment and thermo-chemical treatment. The purpose of the reinforced gears should also be taken into account.

It is advisable to use both devices described for burnishing in any order. In order to enhance the improvement of the tribological properties of reinforced wheel teeth, it is additionally recommended, after performing the pressure burnishing with both devices, to apply short-term shot peening to obtain a particularly favourable relief of the operating surface of the teeth of the reinforced gears.

The application of the described surface work hardening treatments in practice allows for a significant improvement in the durability of the gears in terms of increasing the tooth breakage resistance, improving the resistance to abrasive wear and fatigue pitting.

The improvement of the tribological properties of the working surface of teeth increases the effectiveness of lubrication and increases the resistance to temporary overloads of the gears during operation and to scuffing, too.

Bibliography

[1] Müller L., Gear trains – designing. WNT, Warszawa. 1979.

[2] Skoć A., Switoński E., Gear trains – basis of operation – geometrical and strength calculation. WNT. Warszawa. 2017.

[3] Adamecki D., Grzegorek W., Mikuła J., Mikuła S., Mechanisms of failure of gears in the driving systems of construction machinery and their diagnosis in exploitation conditions. KOMTECH Conference, Institute of Mining Technology KOMAG, Gliwice. 2020.

[4] Przybylski W., Machining by the cold work, technologies and instrumentation. WNT, Warszawa. 1979.

[5] Blicharski M., Surface engineering. WNT, Warszawa. 2009.

[6] Dobrzański L. A., Basis of the shaping of surface and properties of metal materials. Publishing House of Silesian University of Technology. Gliwice. 2007.

[7] Kula P., Surface engineering. Monograph. Lodz University of Technology. Łódź. 2000.

[8] Dobrzański L. A., Basis of material science – metal science. WNT, Warszawa. 2006.

[9] Kubiński W., Materials sciences. Publisher, AGH, Kraków. 2010.

[10] Łunarski J. (red), Cold work and another methods of surface treatment. Scientific Journal of Rzeszow University of Technology. Rzeszów. 1987.

[11] Łunarski J. (red), Fatigue strength of machine parts after chosen methods of surface machining. Scientific Journals of Rzeszów University of Technology. Mechanics, No. 17, Rzeszów. 1988.

[12] Patent PL 237645. Tool for surface machining of toothed gears by cold work.

[13] Patent declaration No. P427738. Device for toothed gears strengthening and particularly helical gears.

[14] Patent declaration No. P429855. Device for the surface strengthening of toothed gears with curved tooth line.

[15] Patent declaration No. P437079. Hydraulic disc for the dynamic cold work of machine elements with the control of surface processing.

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GENERAL CONCEPTS IN THE LABELLING PROCESS

OGÓLNE POJĘCIA W PROCESIE ETYKIETOWANIA

***Summary**: The present paper is the first part of a series of articles, introducing the comprehensive issue of an attempt to compare the work of detection sensor with the ZFV vision system in the process of labelling the packaging.*

***Keywords**: label, labeling, packaging, detection sensor, the ZFV vision system*

***Streszczenie**: Artykuł jest pierwszą częścią wprowadzającą w obszerne zagadnienie jakim jest próba porównania pracy czujnika detekcji z systemem wizyjnym ZFV w procesie etykietowania opakowań.*

***Słowa kluczowe**: etykieta, etykietowanie, opakowania, czujnik detekcji, system wizyjny ZFV*

Introduction

More and more products have become recently delivered to the customers in protective or in bulk packaging. The customer expects information about the product's country of origin, its composition, way of functioning etc. All mentioned information is placed on the packaging in a form of label. Due to the automation of the way of filling of packing the products, the increase in the performance of manufacturing lines has been observed; it resulted in the necessity of increasing the rate of placing the labels.

At present, the manual labelling of the packaging is employed only in the case of the products with complicated shapes, or in the small-series production, up to 10 000 pcs. The mentioned value is caused by psychomotor limitations of human body construction. They are individual features of every employee; therefore, the discussed value varies between 15 and 30 labels per minute what gives about 6 000÷10 000 labels during one 8-hour shift. Above the mentioned quantity, it is more profitable to use machine; in consequence, we obtain a stable performance and precision of labelling. Marking of the packaging is a necessity, both from the point of legal rules and the marketing aspects.

For majority of the products, the way of placing the labels is strictly specified in the national or international standards, e.g. in food and cosmetic industries. The example may be the Council Directive 76/211/EEC of 20 January 1976 [1].

Aesthetic and attractive packaging is nowadays indispensable for the customers. Labelling is, therefore, the important part of the total manufacturing line. The choice of the components of the production line is dependent on the expected performance, shape as well as volume of the packaging and the type of the dosed medium.

Automation of the process allows obtaining a high effectiveness and repeatability of precision of label placing. It is reflected in a small number of defectively marked packaging, increasing thus the positive economic balance of production. Consequently, when designing a manufacturing line, a big attention is paid to precision, repeatability and universality. Designing of machines or manufacturing lines requires individual approach to each device as well as to the successive stage of production. There are available different types of labels in the market and, also, different systems of their positioning on the labelling machine.

The purpose of the present work was to develop the stand, enabling positioning of the packaging with the use of the sensor, and to compare its functioning and that of the earlier employed vision system. The implementation of the mentioned above aim could help obtaining the answer to the question: which system of positioning is most suitable for a given type of label.

To understand better the essence of the present work, the attention of this part has been focused on definition of certain general concepts, relevant to the submitted elaboration. They include as follows:

- measurement error,
- technical device,
- marking of the product,
- labelling,
- the methods of label positioning,

- environment conditions during the implementation of measurements.

To have the possibility of comparing some phenomena each other, it is necessary to ensure the uniform conditions of environment during obtaining the results. According to contemporary physics, the process of measuring device's effect on the examined object, occurring at time and space, as a result of which the information about the object's properties is obtained, is called the measurement. There are some types of measurements employed, including, *inter alia*:

- continuous,
- discrete.

The continuous process is the process which supplies the results in the continuous way; they may be available on the current basis, e.g. speedometer in mechanical vehicle, or with a certain delay, e.g. room thermometer reacting with the delay to the change of temperature.

Another type of measurement is the *discrete* measurement (from Latin – *discretus* – separate). It is a sort of measurement which supplies the results in a given site. Such measurements may be conducted cyclically or irregularly. The example of such type of the measurement includes measurement of body temperature with the use of medical thermometer or control of oil level in a car, using dipstick.

To perform the measurement, we need the appropriately calibrated measuring stand, containing a device and enabling the repeatability of measuring operation. Each measurement has a measurement error which is a deviation from the unit result of the measurement as compared to real value; the mentioned value is generally known. We do not, however, treat it as an error but as inherent factor of measuring process. We can distinguish the following errors:

- rough
- systematic
- random
- in control point
- in zero.

The rough error occurs usually due to inattention of the operator or the change of the measuring environment. It is removed from the table of the results during the analysis of the series of measuring data.

The systematic error repeats constantly or in foreseeable way. It is a result of inaccuracy of measuring device and measurement method. It is treated as a correction to the result.

In repeatable measurements, we may find **the random error**, resulting from the difference in temperature or motion of the air. It may be determined during the repeatability test for the results obtained from a given measuring device.

In the control point

In the control point, we may meet the error of the measurement of measuring device or measuring system at the specified value of the measurand. For example, we may indicate the errors stated during the calibration of the measuring device in the specified points.

In the case when the specified measured value is closely approximate or equal to zero, then we have to deal with **the error in zero**. For example, the mentioned error for electronic balances means the stability of zero indication. The discussed stability may be important during long-lasting measurements of the same sample. We should note that the smaller the weight of the sample is, the higher is the participation of "zero error".

Technical device is specified as the object, enabling performance of the defined process, according to its destination, being often a set of connected mutually parts. The mentioned elements create the integrity, serving for the specified functions of a given process. It concerns, for example, information processing. Such device has a specified form of construction, depending on the purpose of destination and the satisfying work parameters. Hence, the discussed equipment may be classified according to destination:

- machines, i.e. the objects for energy transformation or performance of specified mechanical work;
- the tools – they are the equipment of man or of a given machine, so they affect directly the object of the work;
- fitting – a set of auxiliary elements, assembled in machines or in devices, facilitating the correct and indispensable functioning;
- equipment means the technical object that is dependent on the presence of electromagnetic field or supply of electric current; it serves for production and transmission or measurement of intensity of electromagnetic field.

Marking

Marking of the product is obtained *via* application of label, which was earlier called a tag. It is a company mark, trademark, illustration or another written, extruded or copied sign, or the image, placed on the packaging by another method, or enclosed to it. The mentioned mark may have a form of paper or film product; it is directly fixed to the product or placed on it in order to identify or specify its contents. Labels serve also, more and more frequently, for marketing activity, when promoting the product and attracting the attention of the customers. To this end, the designers of the labels suggest more and more differentiated shapes and they are constantly seeking for new materials to be used as the labels. They conduct also the experiments with the printing technology employed in their production. It generates many new problems to be solved owing the labelling machines and creates their additional classification according to the type of the labels [2]. We may distinguish the following types of the labels:

- in-wet glued
- self-stick
- in-mould (IML)
- shrink sleeve
- bands
- transparent

- multi-page
- reactive (smart)
- VOID type
- PEEL-OFF
- collectible.

In-wet glued label may be historically called as traditional. At the past, the glue was applied in a wet form on the packaging. Since the seventies of the 20th century, there has been observed a strong change of in-wet labels into the self-stick ones.

The **self-adhesive** label is printed on the self-adhesive material, e.g. on self-adhesive paper or film. The substrate is covered with a layer of glue from the side being stick to the labelled product and the glue is protected by the protective layer after removal of which the label is ready to be glued. The labels of this type are most frequently performed on a ribbon rolled into a roll. Such form facilitates automatic feeding on labelling machine. To make the appearance of the labels more attractive, and to prolong their stability, they are coated with a transparent film or they are covered with UV lacquer.

IML (in-mould) labels are employed, *inter alia*, in food packaging such as e.g. cheese, fish, yoghurts etc. At present, the discussed type of label is performed on a substrate made from plastic. It is the same plastic as the packaging. It is introduced into injection mould and embedded in the packaging during its manufacture. Printing techniques employed in production of IML labels include: sheet offset, inks preserved by oxidation or UV radiation, intaglio printing, rolled narrow-band offset, with the use of UV inks and flexographic printing with the application of UV inks, as well.

Shrink (heat-shrinkable sleeve) label is a contemporary type of label, performed on plastic substrate, in a form of shrink sleeve which is applied on packaging, cut and shrink as affected by temperature, so it strictly adheres to the packaging, e.g. glass bottle. The mentioned label may also play protective functions on the principle of plum, protecting against opening of the product. Sometimes, it is used for combining two products within the frames of promotion: two in price of one, or added to a given product when the other one is gratis. Owing to the fact that the SSL label may cover the total product, it strengthens the rigidity of the product's packaging. In the so-called multipacks, i.e. bulk packaging, it is possible to employ thinner walls in the packaging as well as to make the attractive decoration. The discussed labels are printed inside what protects the printing from wear. Usually, they are produced from the following films: PVC, PET, oriented PS. The films of 50 μm thickness are most frequently used for production of the mentioned above labels [3].

Bands, being sometimes used wrappings, are dry labels, destined for marking of round surfaces such as cables, pipelines or pipes.

We meet also the labels with mirror printing on transparent film. The adhesive is applied on the printed side and after gluing of the label, the **transparent** film becomes simultaneously the protection of printing.

To facilitate placing of a big quantity of text, e.g. in few languages, the **multi-page** labels are employed. They are folded in accordion way and are laminated at the top, with the possibility of designing a very small handle, making opening easy, sometimes with the additional short story or image for the children.

The label, which reacts to the changes in the product's environment, and by this, bears specified information on the product, is called **reactive** label. It is most frequently employed on food packaging. The examples of such type of labels include the labels with printing made by thermochromic ink on bee packaging. In the case when the product is properly cooled down, the proper inscription appears. The labels with temperature identifier (Time Temperature Indicator – TTI) are overprinted with UV radiation-reactivated ink in the packaging process and they change their colour irreversibly if the temperature exceeds e.g. 5oC. They inform, in this way, the consumer that the product was not correctly stored in the supply chain. The label with the silver nanoparticles will change their colour as affected by hydrogen sulphide and by this, it signalizes that a given product is deteriorating.

Plumb used in a form of label, applied in the protection of cupboards, doors or bottles is called **VOID** label. It occurs in two forms: dirtying and non-dirtying. The dirtying form leaves the trace on the plumbed surface whereas the non-dirtying one leaves the trace only on the plumb in a form of inscription reading: VOID OPEN or another one, signalizing infringement of the plumb.

PEEL-OFF is a technology allowing peeling away and repeated sticking of the label one on another: it is used on the products with a small surface and, simultaneously requiring a lot of information to be placed on the packaging for the user.

To encourage the customers to buy the products, their producers employ sometimes the mentioned label as the so-called collector's label. In such case, it appears as a piece of film or paper, and, it is most frequently self-sticking what facilitates its affixation to a flat surface as e.g. in the collector's book.

Labelling is an operation of applying the label on the product. It is performed with the use of device, called labelling machine. It is a mechanical device furnished with the following systems: driving, detection of labels, detection of packaging and positioning of the product. The most frequently employed labels include the self-sticking ones, those printed on paper or film, die-cut and remaining on silicone liner paper after removal of unnecessary openwork. The labels without glue require separate glue applicators. The labels with glue without liner (linerless or liner-free) have not found a wider application due to technical difficulties with their feeding.

The industrial labelling machines are employed mainly during series production intended for self-sticking labels. These latter are the most often chosen method for marking of the products due to their universality. Depending on the needs, the discussed machine applies the labels on any part of packaging. Owing to this ability, the discussed equipment ensures constant and measurable profits and a high increase of the manufacturing efficiency, with the relatively low investment outlays. The constructional solutions of labelling machines can be distinguished according to the following aspects:

- **work of labelling machines:**
- — automatic labelling machines with a high performance, working with transporters in manufacturing lines;
- — semi-automatic labelling machines where the product is manually delivered to automatic wrapping device;
- — manual wrappers for manual applying of precisely positioned labels;
- — applicators without positioning of the packaging and labels for manual downloading of the labels;
- **implementation of liner drive with the labels:**
- — direct without wrapping;
- — direct with the wrapped roller,
- — liner of pulling roller with the additional wrapping system;
- — liner of feeding roller with the additional wrapping system;
- — liner of the feeding and pulling roller with the additional wrapping system;
- **detection of labels:**
- — optoelectronic
- — mechanical
- — volume and ultrasound
- **implementation of packaging wrapping:**
- — manual;
- — with drive from label liner;
- — with drive from the engine of label drive;
- — with drive from the independent engine;
- **implementation of winding the used label liner:**
- — liner from the engine of the main drive and belt transmission with slippage of coupling with friction belt and wheel;
- — liner from the engine of the main drive, belt transmission and clutch on roller for removal of used film.

The submitted methods of classification of labelling machines facilitate the choice of the equipment, considering the type of label and packaging and the expected performance.

Summing up

In the process of labelling, it is important that the label is properly applied on the packaging. To implement it, there is a need of correct positioning the packaging in relation to labelling head. The application of sensors allows counting, positioning, detecting of shape and determining the level of the packaging contents and even detection of undesirable elements.

Literature:

[1] https://eur-lex.europa.eu/legal-con tent/PL/TXT/HTML/?uri=LEGISSUM:l32029&from=PL [dostęp: 4 września 2021] (available since 4 September 2021)

[2] https://sjp.pwn.pl/slowniki/etykietowanie.html [dostęp: 18 września 2021] (available: since 18 September 2021)

[3] https://pl.wikipedia.org/wiki/Etykieta_(marketing) [dostęp: 2 październik 2021] (available: since 2 October 2021)

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RYSZARD MICHALSKI – FATHER OF MACHINE LEARNING

RYSZARD MICHALSKI – OJCIEC UCZENIA MASZYNOWEGO

Professor Ryszard Michalski was the Pole who had very big achievements in the currently fashionable area, i.e. machine learning, being the key to artificial intelligence (AI).

The mentioned scholar gained mainly his reputation and a wide influence on the modern science in the USA where he worked and lectured at University of Illinois in Urbana-Champaign and since 1988, at George Mason University where he created Machine Learning Laboratory (Fig. 1), one of the leading scientific centres of this type in the world.

Before it happened, he had obtained education and his way to the first professional titles and scientific degrees was somewhat untypical.

Fig. 1. Professor Ryszard Michalski at his work place. Source: Wikipedia

He commenced the studies in 1954 at Krakow University of Technology which did not have then the Faculty of Electric Engineering. As the interests of Ryszard Michalski were definitely aimed at electrical engineering and, later, computer science, he moved to Warsaw University of Technology and in 1959 he obtained there the BSc. degree in electrical engineering. His further studies were continued in Petersburg (being called then Leningrad) where he obtained the MSc degree (1961) at the University of Technology. After coming back to Poland, he began to work (1962) at the Institute of Computer Science of Polish Academy of Sciences (PAN). In 1969, Ryszard Michalski defended successfully his doctoral thesis at Silesian University of Technology and commenced his work at the Institute of Automation of PAN.

During the mentioned above period, together with Jacek Karpiński (being known as constructor of minicomputer K-202) he constructed the first Polish Perceptron - the learning system, intended for recognition of manually written letters. I was also involved in construction of learning perceptrons (for recognition of Polish speech) and when I had the opportunity to meet personally Prof. Michalski, I asked him some questions concerning the mentioned device. He had a very modest and self-critical approach to his work, oppositely to Jacek Karpiński who praised his own achievements in his numerous autobiographies as being the global range event. The future appreciated, however, Prof. Michalski... When Prof. Jerzy Pniewski from Physics Faculty of Warsaw University instructed him with the task of constructing perceptron for recognition of

Fig. 2. The first visit of Prof. Michalski at AGH.
Photography from the private collection of the author of this paper

photos connected with the reactions of elementary particles (which Prof. Pniewski received as a result of cooperation with CERN) which had to be analysed and classified, Karpiński constructed the system KAR-65 but it did not meet the expected hopes.

Prof. Ryszard Michalski could not see the possibility of "spreading the scientific wings" in Poland and in 1970, he migrated for the United States of America where, initially, he worked at Illinois University in Urbana-Champaign and since 1988 at George Mason University. In the both mentioned universities, he created the teams of scientists, developing different methods of machine learning. Many methods of machine learning, as developed and utilized until now, have been created just in the mentioned above teams, and Professor Ryszard Michalski gained the commonly used title of "father of machine learning".

His work commenced opening of new areas in the field of learning strategy and the representation of knowledge. The important area of discoveries by Prof. Michalski included combination of genetic algorithms introduced to computer science by John Henry Holland, the processes of simulated evolution and the problems of machine learning. The class of evolutionary calculation process, as introduced by Prof. Michalski, being called *Learnable Evolution Model* has been a very meaningful scientific achievement, being imitated later and cited by many researchers all over the world. Theory and methodology of induction learning was another known and appreciated scientific achievement of Prof. Michalski. The mentioned theory perceives induction learning as heuristic search in space for symbolic descriptions, generated by the application of various rules of concluding in the initial observation statements. Prof. Michalski created the mentioned above theory and then, he employed it in the area of conceptual analysis of data what was undoubtedly a pioneer work.

His original ideas, undertaken later by many researchers, was introduction of conceptual grouping and also, ingenious integration of quantitative and qualitative discoveries, utilized later in widely known ABACUS system.

When looking at the list of publications of Prof. Michalski deriving from the discussed period, it is easy to notice that almost all these papers contain the Polish-sounding names of Professor's co-authors. It is not accidental – many Polish IT specialists who left for US for a permanent stay or for the time-limited practice, sought the help at Professor Michalski – and he gave them his generous assistance, including them, *inter alia*, to his research teams and to his publications.

At a certain moment, Prof. Michalski noticed that many of his young Polish protégés were my pupils: they wrote their MSc. and also, some of them, PhD dissertations under my guidance. It is worthy to mention that in the period of 1980–2000, there were developed more than MSc papers and 38 PhD dissertations under my guidance; the so-called "injection of a fresh blood" was noticeable and young, clever and well-educated people took an advantage from the possibilities which were generated after the political transformations in Poland (1989). They left for abroad, mainly to the US where they had undoubtedly the greatest chance to make the scientific career.

The mentioned above phenomenon had caused that Prof. Michalski assumed creation of a new AI in Krakow AGH and decided to visit it. He wrote a letter to me and then, he arrived to Krakow and visited AGH – the university which he heard much about but he has never got to know it earlier.

He came for the first time in 2001 (Fig. 2) and met with the scientists and doctoral candidates of AGH; the mentioned meetings had a character of seminars.

Fig. 3. Exchange of the authors' books.
Photography from the private collection of the author of this paper

Fig. 4. Meeting with Professor Michalski in Washington (Lincoln Mausoleum in the background). Photography from the private collection of the author of this paper

The joint work was implemented, however, in another area, because Prof. Michalski was the follower of the comprehensive transfer of the resources of Polish libraries to computer databases to which the readers could have an access *via* Internet website. Meanwhile, I performed similar practical activity in the Chief Library of AGH. Owing to the mentioned exchange of ideas with Prof. Michalski and mutual stimulation, many valuable books (especially of those ones, being "read out" frequently by the students almost to the physical destruction) were collected in a digital form in the computers, functioning at the library of the Krakow University of Science and Technology (AGH). It is worthy to mention that the first book which was publicly available in the mentioned above manner was my monograph: "*Neuron networks*" (1993). It is up to now available in the Internet under the address: http://winntbg.bg.agh.edu.pl/skrypty/0001. It deserves attention that the number found in the above address is 0001 – it is evidence that just this book commenced everything!

The total activity of digitalization of paper books at AGH and other Polish universities (libraries' cooperation is very effective!) resulted from the advices and suggestions of Prof. Michalski – it is the reason for mentioning this fact in the present paper.

After the series of Prof. Michalski visits in Poland, the time for revisits came. In the summer of 2004, I managed to place some my lectures at the scientific conferences which were held in the USA in nearby cities and in the favourable time coincidence. So, I arrived to Washington and met Prof. Michalski on the American land (Fig. 4).

Prof. Michalski's laboratory in George Mason University was situated only 20 miles (30 minutes by car) from the city, so there was also sufficient time for scientific problems as well as for visiting of tourism objects.

Unfortunately, it was our last meeting... In 2007, Prof. Michalski passed away. But he left a significant group of his pupils and graduates, so the scientific contacts with my group at AGH lasted after his death and they are alive today. His silhouette deserves undoubtedly the cognition and respect. That is why I have developed the present paper.

I helped to facilitate these contact as I was then the Rector of AGH, and, additionally, the tutor of doctoral studies at the Faculty of Computer Science. The mentioned contact occurred to be very successful, so in the 2000, Prof. Michalski visited AGH again. We exchanged then the books: Prof. Michalski gave me his book: "*Machine Learning and Data Mining*" (it is presented at Fig. 3 and is recognisable in the lists of the most important publications on AI). I offered him my book "*Computer-based analysis and image processing*" which was the first Polish handbook on the problems concerning *computer vision*, being very interesting for Prof. Michalski.

We corresponded later intensively on scientific problems although, unfortunately, I didn't manage to write a publication jointly with Prof. Michalski. I regret very much because it would be a great ennoblement for me. Unfortunately, it happened so that always when a new, unusual scientific concept was born in our correspondence, then, a young scientist appeared immediately (at AGH or in USA) and he needed urgently a well promising subject for doctoral dissertation as it was the conditions of his/her further career... It was the period when more and more talented women appeared in the field of computer science. Summing up, we have not created any joint publication although we were very close to the so-called "dotting the i's.