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Review of Magnesium Alloys Used in the Manufacture of Wheels for Light Vehicles

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ABSTRACT

This article provides an overview of the materials used to manufacture magnesium wheels for light vehicles. The analysis was conducted with the aim of developing a new, efficient technology for molding magnesium alloy wheels for light vehicles from preforms cast into metal molds. The knowledge accumulated so far on materials and their properties for the production of magnesium wheels will allow the design of a new technology for molding rims from materials of superior quality and durability. Currently, magnesium wheels are mainly produced from cast magnesium alloys and magnesium alloys for forming. Cast magnesium alloys used for magnesium wheels include AZ91, AM50, AM60, AE44, ZK61, ZE41, EZ33, EQ21, WE43 and the newly developed Mg-2.96Nd-0.21Zn-0.39Zr alloy. Magnesium metal-forming alloys used for magnesium wheels include AZ31, AZ61, AZ80 and ZK30, ZK60. The study includes an analysis of their properties and application examples.

Keywords: magnesium alloys, casting alloys, wheels, light vehicles, metal forming alloys.

INTRODUCTION

The development of magnesium-based light metal alloys is an issue of key importance for economic development, especially in the context of modern means of transport [1]. The use of these alloys in the automotive industry plays an important role in reducing the weight of vehicles while improving a number of vehicle technical parameters (Fig. 1).

Exceptional strength and low weight make magnesium an attractive construction material for car manufacturers. Forecasts suggest that magnesium consumption in a modern car may soon exceed 100 kilograms [3]. In the context of increasingly restrictive exhaust emission standards and development of electromobility, vehicle manufacturers are intensifying work on the development of lightweight structures, which contributes to the increase in demand for magnesium alloys [4].

One of the main applications of magnesium in the automotive industry is lightweight vehicle wheels, which are used in various types of vehicles including cars, motorcycles, bicycles and wheelchairs [5]. Magnesium wheels are an important part of modern solutions. Their production is based on the use of magnesium alloys, which are characterized by an extremely favorable set of properties. The main reason for using these alloys is their low density. Magnesium alloys are 30 to 40% lighter than popular materials such as steel

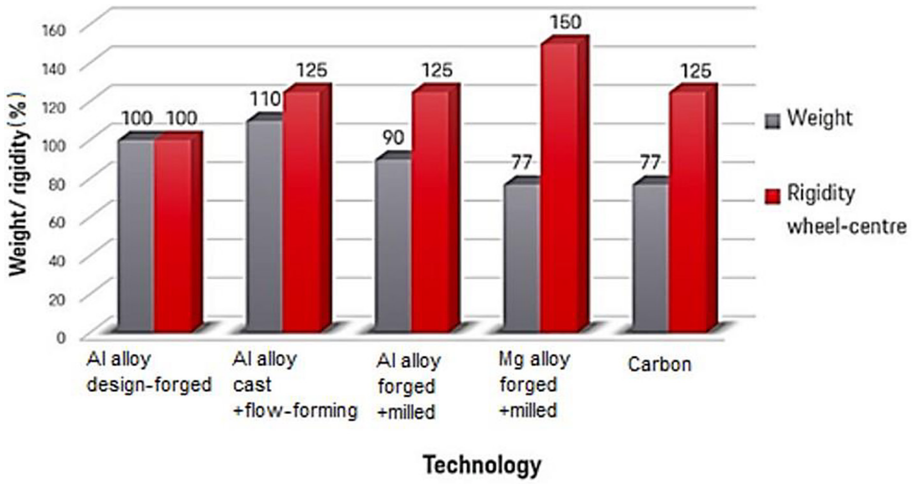

Fig. 1. Weight/rigidity comparison of certain wheel materials and technologies [2]

or aluminum [6]. The reduced weight translates directly into vehicle performance, reduced fuel consumption and improved overall handling. The high mechanical strength that magnesium alloys have makes them excellent for use in the manufacture of magnesium wheels. The tensile strengths of alloys such as AZ91, AM50 and AM60 range from 180 to 300 MPa, while WE43 alloy can reach as high as 400 MPa [7]. Such values attest to their excellent mechanical properties, making them an attractive choice for manufacturers (Table 1).

Magnesium alloys are also characterized by significant resistance to high temperatures, making magnesium wheels retain their performance under extreme conditions. In addition, these materials exhibit vibration damping capabilities, which translates into driving comfort. Their unique properties, such as the ability to reduce vibrations and significant specific strength, make them even more valuable [9]. An additional advantage of magnesium alloys is their relatively simple processing. This means that magnesium wheels can be designed in a variety of shapes and styles to meet both aesthetic and functional requirements. This gives manufacturers a great deal of freedom to create innovative designs [10]. Today, magnesium wheel manufacturing uses a variety of technologies, including machining, shape casting and metal forming, including die forging, extrusion and rolling. While each of these technologies has its advantages and limitations, magnesium casting is currently the most widely used technology due to its availability and favorable price. Magnesium wheel casting has high dimensional precision; however, it can exhibit manufacturing defects such as cavities or porosity, which can affect susceptibility to cracking during high-speed impacts [8]. Magnesium wheel forming, on the other hand, is a challenging task due to the narrow range of processing temperature parameters and sensitivity to strain rate. The process of forming magnesium

Table 1. Comparison of mechanical properties of Mg alloys [8]

Performance	Unit	Mg	AZ91	AM50	AS41	AE42
Density	g/cm^3	1.74	1.81	1.77	1.77	1.79
Specific heat	kJ/kg×K	1.025	1.02	1.02	1.02	1.02
Thermal conductivity	W/m×K	154	51	65	68	84
Melting temperature	°C	650	598	620	638	625
Solid-liquid conversion temperature	°C	650	420–435	420–435	420–435	590
Conversion heat	kJ/kg	368	370	370	370	370
Tensile strength	MPa	165–205	240–250	210–230	215–240	230
Yield limit	MPa	69–105	160	125	140	145
Elongation rate	%	8–11.5	3–7	10–15	6–15	10–11
Elastic modulus	GPa	45	45	45	45	45
Brinell hardness	-	36	70	60	60	60

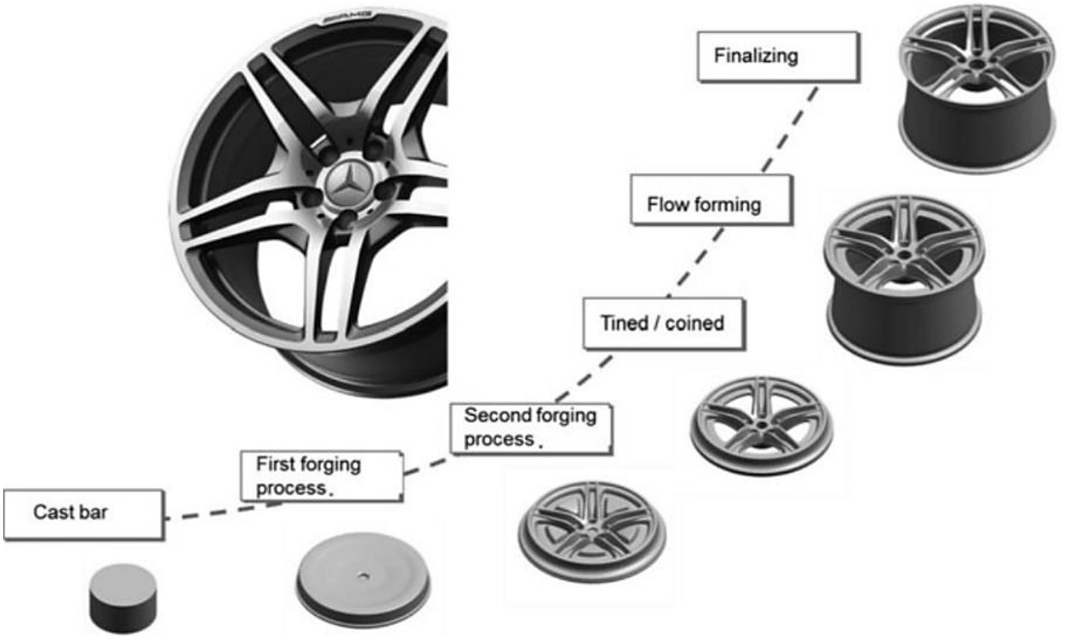

Fig. 2. Forging process [11]

wheels is carried out hot on forging machines, which carries with it low operating speeds and the maintenance of isothermal temperature conditions during deformation (Fig. 2).

Despite higher production costs, forged magnesium wheels have a fine-grained structure and better mechanical properties than cast wheels [12]. The choice of the appropriate magnesium wheel manufacturing technology depends on a number of factors, including cost, mechanical property requirements and the application of the wheel [1]. For the automotive industry, aspects related to durability, corrosion resistance and mechanical properties are particularly important. Therefore, numerous studies are being conducted on various types of coatings that effectively protect the magnesium substrate against cavitation erosion and reduce wear [13]. It is worth noting that magnesium alloys are increasingly popular in all types of transport, due to their unique properties and potential to revolutionize vehicle design [14]. Their developing applications have a positive impact on the efficiency and effectiveness of the automotive industry, and the prospects for this material are promising. The review will help identify trends in the development of magnesium alloys for wheel production and innovations in this field. It will enable the assessment of the advantages and limitations of using magnesium alloys in wheel production, including their strength, lightness, corrosion resistance and durability. This will help to understand under what conditions they are most effective. This will be particularly important in the context of changes in the automotive industry, such as vehicle electrification and the desire to increase fuel efficiency [15].

ANALYSIS OF MATERIALS USED IN THE MANUFACTURE OF MAGNESIUM WHEELS

For designating magnesium alloys, the industry applies an American system approved by the ASTM (the American Society for Testing and Materials) specified in the ASTM B951-10 standard. In general, as far as the technological application is concerned, magnesium alloys may be divided into cast alloys and alloys for metal forming.

The cast magnesium alloys used to manufacture magnesium wheels include AZ91, AM50, AM60, AE44, ZK61, ZE41, EZ33, EQ21, WE43, and the newly developed Mg-2.96Nd-0.21Zn-0.39Zr alloy. The magnesium alloys for metal forming used in the production of magnesium wheels include AZ31, AZ61, AZ80, and ZK30, ZK60.

The AZ91 constitutes the most popular magnesium alloy for casting. It is characterized by good tensile properties and fluidity. Considerable aluminum content (approx. 9% of the mass) gives the alloy low ductility in room temperature [16]. The alloy undergoes precipitation hardening. In order to enhance ductility, the alloy is homogenized within the 415–435 °C range for a minimum of 16 h [17, 18]. Supersaturation is conducted typically within the 415–430 °C range, while aging, depending on the sought after properties may be carried out in the 170–200 °C range [19, 20]. For example, in work [21] AZ91D alloy was used to make motorcycle wheels by forming of die casting and double control forming. The study presents a comparison of microstructures and mechanical properties of samples derived from motorcycle wheels manufactured by means of pressure die casting as well as by a novel method of double control forming from the AZ91D alloy. The novel method consists of the compression of the ingots. Functional properties exceed those obtained by means of pressure die casting.

Due to the fact that in the case of wheels, in addition to low mass, the ability to dampen vibrations is also important, the authors of paper [22] analyzed wheels made from AZ91 as regards vibration modeling in relation to 6061-T6 aluminum and SPFH540 steel. The magnesium AZ91 alloy manifested the best vibration-damping characteristics. Analyzes conducted using the FEM method by the same authors also show that the AZ91 magnesium alloy is the most suitable for use on magnesium wheels in terms of bending and radial loads. In paper [23], the same materials again: 6061 T6 aluminum, SPFH540 steel and AZ91 were compared. The analysis revealed that despite inconclusive results, for light structures, the magnesium alloy is preferred. The subject of FEM analyzes in the context of the AZ91 alloy are also elements of the technological process in the context of low-pressure die casting. In work [24] critical areas were indicated in relation to structural defects (e.g. pores in spokes). Additionally, the adjustment of filling parameters was proposed in order to solve the problem. The authors of publication [25] attempted to optimize the parameters of the same process, in which they analyzed the parameters of low-pressure die casting. Optimal parameters were determined in order to obtain structural homogeneity, reduce shrinkage porosity, and lower dendritic segregation. The most suitable parameters for a wheel made from AZ91D are as follows: filling temperature of 689 °C and filling pressure of 6,5 kPa. In paper [11], it was discussed examples of wheels made from AZ91 and AM60 by means of sand casting and metal die castingas well as pressure die casting. Both advantages and drawbacks of each method were determined. The AM60 alloy belongs to the casting alloys group [11]. It is predominantly used in pressure die casting processes. Its properties are similar to those discussed below for the AM50 alloy. Manganese must be present in order to for the alloy to undergo precipitation hardening. The element is present in the AM60B grade [26]. The study analyzed the AM60B alloy and pressure die casting for the manufacture of motorcycle wheels. The work revealed that the material and technology meet the requirements for motorcycle wheels.

Apart from motorcycle wheels, magnesium alloys may be used to manufacture bicycle wheels. For example, the Shuangye electric bicycle introduced integrated magnesium wheels with six or three spokes. These wheels are lighter than those made from aluminum alloys [27, 28]. The bicycle industry employs the AM60B alloy [29]. The study modified the width of the spoke and the radius of the wheel. Optimized radius parameters were established for the redesigned wheel. The maximum stress was lowered to 65.612 MPa.

The AM50 alloy is intended for cast production, especially for pressure die casting. It is used in the production of structural elements in the automotive industry, electronics, and telecoms. Its chief advantages include very good fluidity, high durability-mass ratio, and very high corrosion resistance. The alloy undergoes homogenization and precipitation hardening [30]. The authors of the work [31] compared the results of strength tests for samples derived from motorcycle wheels made in the DC (die casting) and DCF (double control forming) technologies. It was established that the DCF enables much better properties to be obtained for the AM50A alloy. The authors of paper [32] compared a variety of magnesium alloys in terms of their applicability for the manufacture of wheels. The study analyzed alloys such as: AZ91, AM50, AM60, AZ31, ZE41, EZ33, ZE63, and ZC63. The Multi-Attribute Decision Making (MADM) method was applied. For all cases, the AZ91 alloy proved the most suitable.

In the review type paper [33] selected properties of magnesium alloys, aluminum, and titanium as regards the manufacture of wheels were compared. Additionally, the authors analyzed individual manufacturing technologies for the surveyed materials. Magnesium wheels are characterized by low mass, high specific strength, and resistance to dynamic deformations. One of the chief problems is corrosion resistance. The authors indicated that casting and forging constitute predominant technologies. Pressure casting has also become a developing technology in recent years. The AM60 alloy, the A356 aluminum alloy, and unspecified titanium alloy were selected for the comparative analysis. The analysis revealed that the aluminum alloy manifests the greatest effectiveness (cost-effect ratio) although, magnesium alloy has higher efficiency.

The Mg-4Al-4RE alloy ismostly used in pressure die casting. Its composition includes rare earth elements: a mixture of cerium and lanthanum. The application of this mixture allows hardening with the use of T5 heat treatment. The employment of such a process enables improved tensile strength to be obtained without losing any ductility [10, 34]. The study [35] discussed examples of the application of magnesium alloys in the production of, inter alia, automotive wheels. High costs and insufficient corrosion resistance were indicated as chief barriers to the mass production of magnesium wheels. The Mg-4Al-4RE (AE44) alloy was indicated as the one possessing high strength and ductility both in a room and at elevated temperatures [36]. Authors argued that the introduction of anticorrosion coatings and the development of various casting technologies may broaden the application range of magnesium alloy wheels.

The ZK61 alloy is a high-strength cast alloy grade. The ZK61 alloy was developed to be used in sand casting and Liquid Forging [37]. The content of zirconium facilitates grain fragmentation. On the other hand, Zn enables precipitation hardening. Supersaturation temperature is high and may reach up to 510 °C for 3 h. Aging may be performed in 120 °C for 24 h. Even though it is characterized by high strength, the alloy is not broadly used due to the tendency to form microporous structures when cast. It is also unweldable due to high Zn content. In these work it was outlined the results of studies concerning the impact of yttrium additive upon the microstructure and properties of the ZK61 alloy used for the manufacture of the wheel's hub by means of liquid forging. The study revealed that the best mechanical properties and correct microstructure were obtained for 1% of yttrium additive by weight. The analysis of thermal conditions showed that the best results were obtained for the forging temperature of 380 °C.

The ZE41 alloy is characterized by high tensile strength up to 200 °C [38]. The EZ33 alloy manifests a higher creep resistance and may operate in temperatures up to 250 °C [39]. This alloy is characterized by good fluidity. It is employed in the manufacture of tight castings. A high degree of precipitation hardening was determined in alloys containing Zn and rare earth elements. Maximum hardening while aging is obtained for those alloys where secretions are coherent with the metallic base. Such alloys are applied in the manufacture of engines and gearboxes operating at 120-205 °C. The EQ21 magnesium alloy contains silver and manifests considerable tensile strength at room temperature. It also exhibits good creep resistance up to 200 °C [40]. It also welds well. The good mechanical properties of the Mg-RE-Ag-Zr group, to which EQ21 belongs, make it ideal for the manufacture of critical parts of machines. Owing to the high content of yttrium, the WE43 alloy manifests high flashpoint (750 °C) and strong hardening properties. Its broad application is limited due to its high price [41].

The Mg-2.96Nd-0.21Zn-0.39Zr cast alloy has been recently developed. According to the authors of the study [42], the alloy manifests high strength properties and corrosion resistance as well as high fatigue limit. The alloy may be used for sand casting and die casting. When using the alloy, it is beneficial to apply T6 heat treatment. In this work the results of fatigue tests of samples derived from cast magnesium wheels have been discussed. The wheels were manufactured by means of low-pressure die casting into a steel form (Fig. 3). Then they were tested at the post-casting stage and T6. A fatigue test with controlled deformation was conducted. The results proved conclusively that samples that were heat treated are characterized by considerably higher fatigue

Fig. 3. Magnesium wheels of the Mg-2.96Nd-0.21Zn-0.39Zr [42]

limits. The authors of the work highlighted the effect of hardening and the decline of structural defects (shrinkage porosity) due to heat treatment. The test was conducted with a frequency of 2 Hz with push-roll loading.

Cast magnesium alloys may be shaped by means of casting processes such as continuous casting and shape casting. As far as shape casting is concerned, the following methods can be distinguished: sand casting (Mg-Al-Zn, Mg-RE-Zr, Mg-Zn-Zr magnesium alloys); die casting (due to high temperature brittleness Mg-Zn-Zr group is not applied); pressure casting (application of Mg-Al-Zn, Mg-Al-Mn, Mg-Al-Si, Mg-Al-Ca, Mg-Al-Sr groups); pressure casting with compression, and casting from semi-solid state [30].

The AZ31 and AZ61 alloys are intended for plastic metal forming processes [43]. They deform in high temperatures especially when fine grains are present (<3 μm). They manifest good tensile strength and ductility. Alloy additives - aluminum and zinc - enable precipitation hardening of AZ31 and AZ61, and enhance the granularity of the microstructure. Additionally, the alloys can be reinforced by plastic deformation. The AZ91 alloy is intended for operation in room temperature or elevated temperatures up to 100 °C. The alloy is weldable. Once welded, elements made from this alloy should undergo stress-relief annealing in order to reduce the probability of stress corrosion cracking. The homogenization of the AZ31 alloy is conducted in 390 °C for 22 h, while for AZ61 in 415 °C for 24 h. As far as supersaturation is concerned, the temperature range for the AZ91 alloy reaches 415 °C and for AZ31 it amounts to 450 °C. The maximum aging temperature for AZ61 amounts to 175 °C and for AZ31 it is 300 °C.

Forged magnesium wheels are employed, inter alia, in the aviation industry, e.g. in the hubs of aircraft wheels. Paper [44] refers to the application of AZ31 for that purpose. This alloy was also studied in work [45]. Authors conducted studies concerning the production of aircraft wheel hubs by means of hot forging from magnesium alloys with a diverse aluminum content ranging from 3% to 8% (AZ31, AZ61, AZ80). Their research shows that the selected element possessing specific properties can only be made from the AZ31 alloy.

The AZ80 alloy is characterized by high strength and can be heat treated. It can also undergo plastic metal forming and forging. Semi-finished products are manufactured by means of extrusion. Elements made from this alloy may be operated at room temperature. The high maximum solubility of aluminum in magnesium (12,7% by weight) enhances the precipitation capability of the alloy, favorably with fine $Mg_{17}Al_{12}$ precipitates. The study [46] reviewed methods employed in the manufacture of magnesium wheels, especially AZ80. Forging and flow-forming, forging and rotary compression and extrusion of the perforated charge were discussed. This last method was of particular interest. It was stressed that the application of the method along with T6 heat treatment enables properties that meet automotive industry requirements to be obtained. The work [47] discusses the results of fatigue tests of samples derived from magnesium wheels manufactured from the AZ80 alloy by means of extrusion. The wheels were manufactured by extruding perforated charge from cast rods homogenized at 385 °C for 12 h. The results of fatigue tests were compared to the results obtained for rolled samples. The authors of the work [48] analyzed wheel discs made from extruded AZ80 alloy and the impact of T5 and T6 heat treatment upon low-cycle fatigue. The results clearly suggest that T5 heat treatment offers the greatest applicability as far as low-cycle fatigue is concerned. AZ80 constitutes another alloy used in the production of vehicle wheels [49]. Rivers et al. studied controlled fatigue of samples derived from the spokes of a vehicle's cast wheel made from AZ80. It was proven that the fatigue limit amounted to approx. 98 MPa [50]. The application of magnesium in a vehicle's wheel leads to the improvement of handling owing to the reduction of not suspended mass. The authors of the studies [51, 52] developed a new magnesium alloy based upon AZ80. It manifests excellent mechanical properties. As a result, a magnesium wheel was obtained which is 30% lighter than aluminum wheels. Excellent granularity for continuous casting in the manufacture of wheels was obtained by means of Sr or Ca additive. The Figure 4 shows the manufactured Az80 magnesium wheels.

The ZK30 and ZK60 alloys are intended for plastic metal forming [38]. Semi-finished products are obtained by extrusion and aging or precipitation hardening. They are also intended for the production of forgings to be operated at room temperature, the same as the AZ80 alloy. If fine grains are obtained, the ZK60 alloy may undergo superplasticity. The ZK30 and ZK60 alloys manifest a slightly better forging capacity than other alloys. Typical homogenization conditions for

a) b)

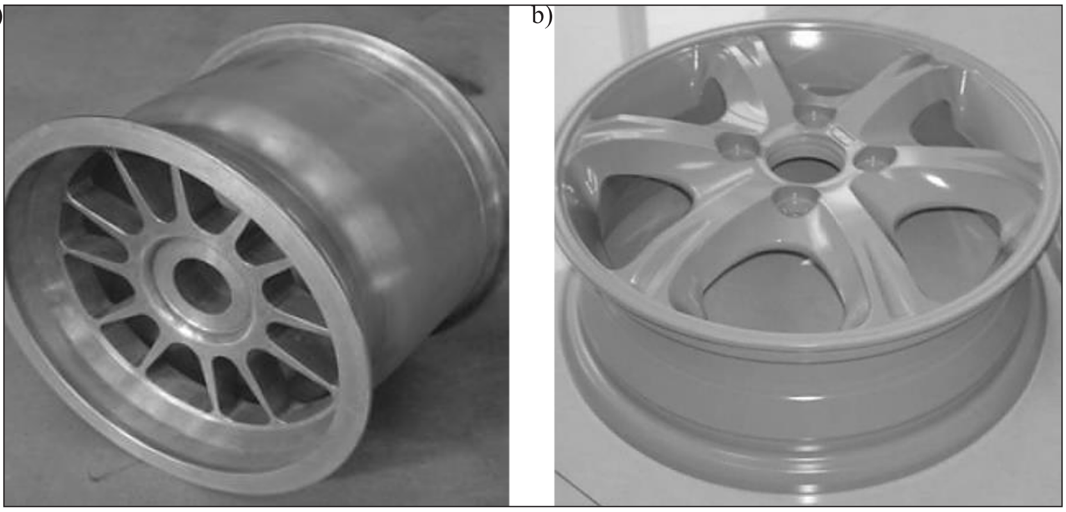

Fig. 4. AZ80 magnesium wheel (a) Magnesium alloy forgings [43], (b) Mg alloy wheels extruded (14×6) J [8]

ZK60 are as follows: temperature of 420 °C, time of 8-12 h. For aging they are 180 °C and 18 h. The authors of work [53] produced a prototype of a wheel forged from ZK30 by means of the same tools used to manufacture an aluminum wheel of the same setup present on the market today [39]. It weighs 6,8 kg (35%) less than the aluminum wheel. The strength is isotropous because deformation stages are uniaxial and stress in all parts of the wheel amounts to 12–14%.

CONCLUSIONS

The article presents the current state of knowledge in the field of materials used in the manufacture of magnesium wheels. It also presents their properties and examples of their use in previously applied methods of wheel manufacturing. The analysis of the problem was carried out on the basis of the literature and available standards as well as commercial offers from magnesium wheel manufacturers. This study systematizes knowledge available in this area. A wide range of magnesium alloys and various technologies is taken into account in numerous analyzes regarding the use of magnesium alloys for the production of wheels. For economic reasons, for wheels with lower construction requirements, but where the weight of the elements plays an important role, alloys and casting technologies are preferred. Therefore, the alloy that is most popular is AZ91 alloy. Its properties and its presence on the market mean that its research is carried out in many aspects. For critical parts such as aircraft wheel components, wrought alloys such as AZ80 are considered. The high cost of this type of products is justified by the high requirements placed on these types of elements. Worth mentioning are modern casting alloys such as Mg-2.96Nd-0.21Zn-0.39Zr, which has both high mechanical properties and significant corrosion resistance. Additionally, new technologies are interesting from the point of view of the analysis, such as deformation and heat treatment of castings in order to improve their structure and properties. The selection of materials with good forming properties for the project will ensure that the final product (wheels) possesses the assumed shape and dimensions and will be of the highest usable quality.

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