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NEW POSSIBILITIES OF APPLICATIONS ALUMINUM ALLOYS IN TRANSPORT

NOWE MOŻLIWOŚCI ZASTOSOWANIA STOPÓW ALUMINIUM W TRANSPORCIE

As it has been reported by Siwiec [49], Helms & Lambrecht [21] the global warming is defined as increase of average temperature of the Earth's near-surface air and the oceans. There are different gases emitted responsible for this effect, mainly: water vapor, CH_4, N_2O and CO_2. According to the recent knowledge, it is supposed that apart from water vapor, CO_2 can have the highest influence on global warming. Carbon dioxide emission sources can be divided into two groups: nature (eruption of volcano, water evaporation, and so on) and anthropogenic. Economic development caused that anthropogenic factor has more share in global greenhouse gases emission. This phenomenon occurrence is connected with transport development, which can be divided into the following groups: aircraft industry, automotive industry, railway transport, construction of ships, aerospace industry.

EU directive concerning CO_2 emission reduction caused many applied technologies to become unprofitable considering environmental preservation. Due to that, there is an urgent need of creating new or modifying existing technological solutions – especially in the field of materials engineering – resulting in further technological development, especially in such branches like automotive and aircraft industry [57]. The idea of decreasing the weight of vehicles is not a new challenge and it has been taken up by many research groups. The effects are mainly observed in reduction of vehicles body weight which directly influences the CO_2 emission decrease. However, in case of vehicles' parts subjected to wear or/and contact fatigue (engine, gears e.g. gearbox) the use of light weigh alloys gives rise to many difficulties. A research in this field may bring another reduction of vehicles' total weight. However, Srivastava et al. [50] holds that the use of titanium, aluminum or magnesium alloys by their nature can cause an increase of wear and lower the contact fatigue resistance.

In this work, the base problem of greenhouse gases emission was explained. Moreover, after market analysis the application of aluminum alloys in transportation was proposed and the potential use in exposition to semi or high load and wear was described.

Keywords: aluminum alloys, light alloys, CO_2 emission, light gearbox, coating, transport

Efekt cieplarniany jest monitorowany poprzez analizę średniej temperatury przy powierzchni Ziemi z uwzględnieniem temperatury oceanów – metoda ta została opisana przez Siwca [43], Helmsa & Lambrechta [16]. Spośród emitowanych gazów do atmosfery największy wpływ na efekt cieplarniany mają: para wodna, CH_4, N_2O i CO_2. Zgodnie jednak z obowiązującą wiedzą przyjmuje się, że najbardziej na ocieplenie klimatu wpływa emisja CO_2 (pomijając parę wodną). Źródła emisji dwutlenku węgla można podzielić na dwie grupy: naturalne (erupcja wulkanów, parowanie wody itd.) i antropogeniczne. Rozwój ekonomiczny świata spowodował, że czynnik antropogeniczny zwiększa swój udział w globalnej emisji gazów cieplarnianej. Zjawisko to jest związane m.in. z rozwojem transportu, do którego zalicza się: przemysł lotniczy, przemysł samochodowy, przemysł kosmiczny, transport kolejowy czy też morski.

Dyrektywy UE dotyczące ograniczeń emisji CO_2 spowodowały, że wiele stosowanych technologii stało się nieprzyjaznych dla środowiska naturalnego. Z tego względu istnieje silna potrzeba opracowania nowych technologii lub modyfikacji już istniejących — szczególnie w obszarze inżynierii materiałowej — w takich branżach jak motoryzacja czy lotnictwo. Idea obniżenia masy pojazdów nie jest nowa i jest podejmowana przez wiele ośrodków naukowych na świecie. Prace te opierają się w większości przypadków na obniżeniu masy nadwozia pojazdu, co ma bezpośredni wpływ na obniżenie emisji CO_2. Jednak w przypadku elementów pracujących w skojarzeniu ciernym (elementy silnika, koła zębate np. w skrzyni biegów) tego typu podejście nastręcza wiele kłopotów. Badania w tym obszarze mogą przyczynić się dodatkowo do obniżenia masy pojazdów. Jednak jak donosi Srivastava [44] zastosowanie lekkich stopów tytanu, aluminium czy magnezu bez zastosowania

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wysublimowanej technologii podniesienia właściwości warstwy wierzchniej może prowadzić do obniżenia odporności na zużycie oraz odporności na zmęczenie stykowe.

W artykule tym wyjaśniono problem dotyczący emisji gazów cieplarnianych oraz przeprowadzono analizę rynku aluminium wraz z potencjalnymi możliwościami zastosowania jego stopów w średnio lub wysoko obciążonych węzłach narażonych na zużycie.

1. Introduction

According to Helms and Lambrecht studies [21], transport industry is responsible for most of the pollution, due to greenhouse gases produced by transport vehicles and oil extraction production.

The highest energy consumption takes place when starting to move a vehicle, as then the engine torque must be high enough to exceed the resisting forces. The highest CO_2 emission is noticed during this time. If vehicles like: cars, buses, trains, ships and airplanes were made of lighter materials, then mentioned torque necessary to start motion would be lower, what would introduce further advantages like energy savings and fuel consumption decrease, implying lower pollution emissions (Fig.1).

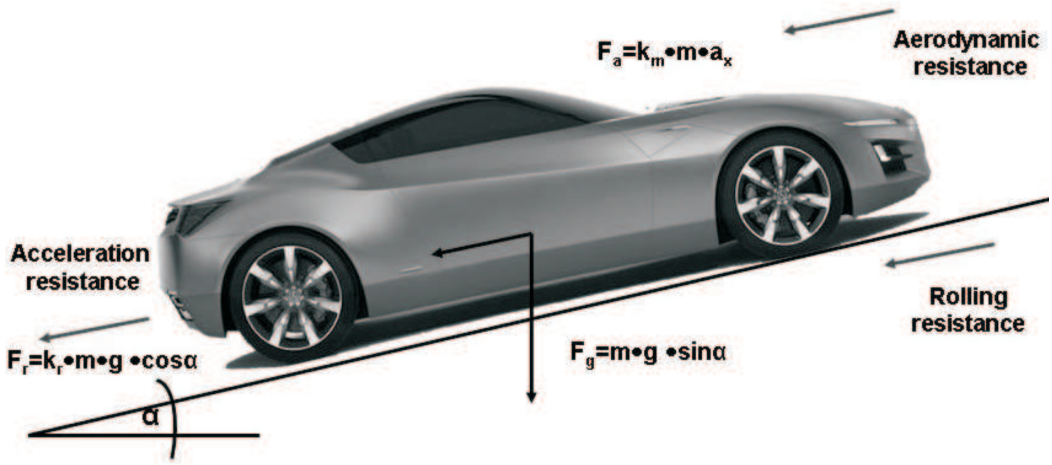

Fig. 1. Forces acting on a car while in a slope

According to the Report by Department of Trade and Industry Automotive, London [6], Aluminum alloys are only 6% of total car composition in average (Fig.2). The main leading materials are steels, plastics and rubber. From this point of view, there is a possibility that the share of aluminum alloys in automotive industry could be increased and cause rational effects.

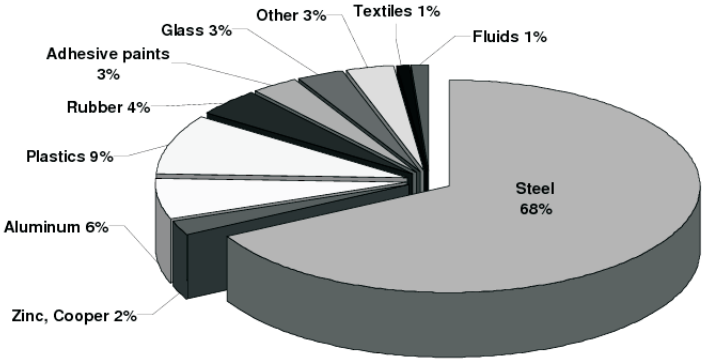

Fig. 2. Average composition of a car

2. Aluminum Market

Aluminum is one of the lightest metals of a specific weight equal 2.7g/cm^3, and the most abundant in the Earth crust. Ancient Greeks and Romans knew it in aluminum salts form. It was mainly used as dyeing mordant until Hans Christian Oersted received a pure form of aluminum in 1825. Two years later, in 1827 Friedrich Wohler obtained pure aluminum by treating an anhydrous aluminum chloride with potassium.

There are about 250 different minerals found in nature, in which aluminum is presented [32].

From economical point of view, the most important aluminum production is from bauxite. Since the 1950's an increase of aluminum production has been observed due to the economic boom and now it is estimated to about 22.3 thousand tones (Fig.3) The largest aluminum producer is Australia with 30% of the total world production. China's production covers 9% of the Global Market. It is in the six position and still increases (Fig.4) [60]. The Aluminum Association forecast informs [2], that China will reach 15 million metric tones in 2008. According to LME analysis (London Metal Exchange) the aluminum price has increased about two times over the past six years, and oscillates between 2800 to 3100 $/ton. Simultaneously, the price of iron was dramatically increasing. Aluminum alloys become attractive materials for applications in the fields of transportation, even if their prices slightly increase, what was not so obvious a few years ago. It was predicted by Miller [33] that the trade expansion of aluminum in automotive industry would be limited only due to the cost level.

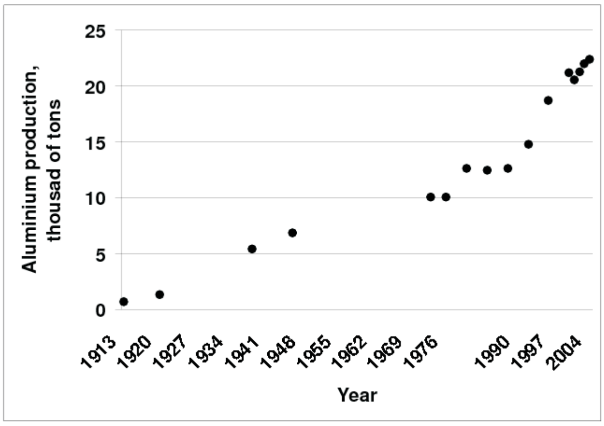

Fig. 3. World production of aluminium

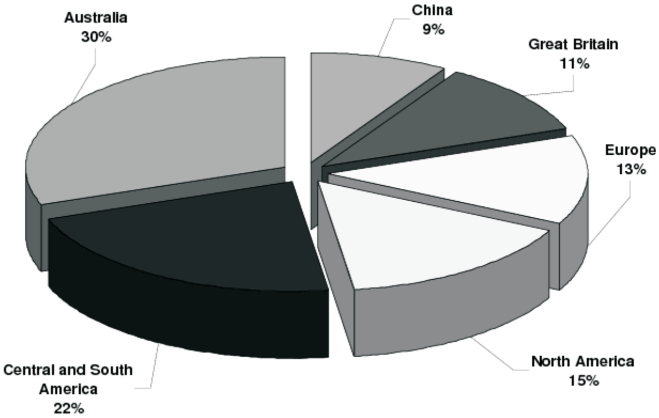

Fig. 4. Principal aluminium producers

3. Aluminum for special application

Brades and Brook [4] reported a limitation of pure aluminum application caused by poor mechanical properties, like Modulus of Elasticity (70 GPa), which is three times lower than for steel (210 GPa). However, aluminum is circa three times lighter, what revealed many new possibilities of applications and discovered a new potential similar to titanium and magnesium alloys, which are used in civil and military aircrafts [35,36]. An addition of different chemical solutions together with heat and/or mechanical treatment can modify the morphology and change mechanical properties in consequence. The following mechanical properties improvement phenomena, proposed by Hirsch [22], Hornbogen [23], Khan and Starink [26] can be distinguished:

- solid hardening strengthening,
- strain hardening by cold rolling,
- strain hardening by heat treatment,
- strain hardening by dispersion strengthening.

This phenomenon is occurred mainly due to following reinforcement mechanisms:

1. Dispersion strengthening according to the Orowan's formula:

$$\tau = \frac{Gb}{L} \tag{1}$$

where:
τ – shear stress,
G – shear modulus of the matrix,
L – particle spacing.

2. Grain size according to the Hall-Petch relation:

$$R = \sigma + \frac{k}{\sqrt{D}}, \tag{2}$$

where:
R – tensile yield,
σ, k – constant,
D – grain diameter.

3. Yield strength vs dislocation density according to the following formula:

$$R = \sigma + \frac{\alpha G}{\sqrt{\varphi}}, \tag{3}$$

where:
α – constant from 0,3 to 0,6;
σ – constant,
G – shear modulus,
φ – dislocation density.

From this point of view, aluminum alloys are widely used in domestic, automotive and aircraft industry. The applications in automotive and aircraft industry still increases. The comprehensive study by Miller [33] and Heinz [20], shows that for instance Hoogovens Aluminum develops aluminum alloys applications in auto body sheet and airframes. It is mainly done due to vehicle weight reduction necessity, what obviously results in lower fuel consumption and implies environmental impact decrease by fuel efficiency rise.

A vehicle weight reduction by 10% introduces 8-10% fuel economy improvement, what is a result of synergism effect, which depends on maintaining the same vehicle performance with a smaller engine. Additionally, taking into account the higher corrosion resistance of aluminum alloys in comparison with steel, they could replace them in most supporting structures and engine parts. The U.S. Army estimated that under normal economy conditions, the real cost of fuel including cost of supply, is approximately 13$ per gallon, Lipsitt et al. [28], but this value increases even to 400$ for gallon during a war, because of additional fuel logistic system. According to the U.S. Army forecast, it is assumed that the future 15-20% vehicle weight reduction is realistic. It allows to reduce the vehicle's rolling resistance by 5%, and can enhance breaking efficiency, what finally could make it possible to raise fuel efficiency even up to 5%.

Aluminum alloys are divided into two groups: casting and wrought. According to American National Standards Institute designation system for every group reported in Alloy and Temper Designations for Aluminum is well known. However, there is continuous and extended work performed, concerning mechanical properties increase by improving: modeling capability, chemical composition optimization, grain structure and grain structure control. Nevertheless, there many elements produced from aluminum alloys, like: engine covers, wheels, cylinders, head covers, pistons, engine blocks, propellers in turbocharger, body frames, crankcases [31,51]. However, all of them are not subjected to wear contact, due to poor tribology properties caused by low hardness and poor wear resistance.

Recent research reported by Williams and Starke [57], Funatani [10], Salazar-Guapuriche et al. [47], Warner [56], shows that the most probable applications of aluminum alloys for elements exposed to high load and wear (e.g. gearbox) are the following wrought alloys: 2xxx (with Cu), 7xxx (with Zn) named duralumin and 8xxx (with Li) series.

Duralumin alloys have outstanding properties like: high strength to weight ratio, high resistance to stress corrosion cracking and fracture toughness. R_m for Al-Cu and Al-Zn series is about 480 MPa and 570 MPa, respectively. Moreover, Fridlyander [9] reported, that it is the most probable to achieve strength (σ_r) for 7xxx and 8xxx alloys up to 1000 MPa mainly due to amorphous matrix received with homogeneous of nanoscale, nanoperiodic phases. First successful investigation in laboratory scale was initiated by Inoue and Kimura [24] for Al-Ln LTM alloys. Verma et al. [54] reported that 7475 aluminum alloy exhibits outstanding fatigue life properties and the volume is on the same level as other structural alloys applied to aerospace structures. This phenomenon was explained by high dispersion level of precipitates during thermomechanical treatment. Such a homogeneous structure reduces stress concentration on insoluble particles. Recently, Buha et al. [5], reported that applied multistage heat treatments coused improve tensile properties, ductility and fracture toughness. Secondary ageing at 338K after 403K in comparison with to the T6 temper provides an increase in the number density of the η' platelets in 7xxx alloys. These metastable coherent phase platelets on $\{111\}_{rmAl}$ are responsible for maximum tensile properties. On the other hand Ber [3] proposed that to receive the optimum structure of hardened precipitates it is necessary to use stepageing regimes. First lower – and second stage higher temperature. It allows to form Q' and Q" phases structure which is responsible for high strength of 2xxx aluminum alloys. For this case Wang et al. [55] suggested modeling the plate like Q' phase in 2024 aluminum alloy matrix. They applied two types of modeling methods: phase field and cellular automaton methods which are on the grounds of thermodynamics of phase transformation. It seems that it would be a useful tool to forecast the 'tailored" mechanical properties by artificial ageing of aluminum alloys optimization.

Additionally, Rodopoulos [45] indicated that applied surface engineering treatments like: shot peening, laser shock peening or ultrasonic impact treatment increase of fatigue resistance of 2024 and 7075 aluminum alloys, respectively. As it follows from Peyre [40] after laser treatment of 7075 alloy, fatigue limit increases to about 22% and 10% after shot peening in comparison to a sample without surface treatment. The increase of mechanical properties is caused by forming the compressine residual stresses during shop peening of 7449 aluminum alloy in the layer of substrate. Induced residual stress field proposed by Mylonas et al. [37] by taking advantage of numerical simulation model and experimental verification. It has been proved that during shot peening, the value of maximum residual stresses and the interval are contained between 500 – 800 MPa. This differences are connected with the shot velocity and shot sizes.

In 1965 Fridlyander with coworkers [27] discovered a new aluminum alloy with lithium addition, which was distinguished by outstanding mechanical properties. In the USA, NASA started its UVa Light Aerospace Alloy and Structures Technology Program in 1986 [11]. This work emphasized mainly mechanical properties of Al-Li-Cu alloy. It accelerated intensively work on a new ultra light material for aerospace industry. However, in 1990s Al-Li-Mg alloy was used already by USSR for fuselages and pilot cabins of MIG-29 fighters [7].

Aluminium-Lithium alloys is a group of high-advanced ultra light materials with exceptional properties. In comparison to typical titanium alloys or even with other aluminum alloys, Al-Li is distinguished by reducing density without deterioration of strength, toughness, corrosion resistance. Addition of 1% of lithium to aluminum reduces density by 3%, additionally [13,14], the elastic modulus is increased by 6% for each 1% Li added, [32]. Therefore, an intensive research under Al-Li alloys is observed to apply it in the aircraft engineering, among other things mechanical properties are optimized by thermodynamic investigations of different Al-Li systems [12, 15, 34]. Recently, Gasior at al. [16] reported new phase diagram of Cu-Li system which could change Al-Li systems with Cu addition. Together with Airbus reported by Guillaumin [19], Al-Li materials offer one of the best solutions to improve aircraft structure performance. Additionally, results received by Rodrigues et al. [46] proved that Al-Li alloys have excellent fatigue resistance even in comparison with aluminum alloys 2xxx and 7xxx series. It is explained by precipitation strengthening of coherent, spherical δ' (Al_3Li) phase during heat treatment. Moreover, Adamczyk-Cieslak et al. [1] reported that due to the grain refinement of Al 1.6%Li using Equal Channel Angular Extrusion (ECAE), hardness and yield stress increase by 100%.

Even thought, Zakharov [61] marked that the same properties still need to be improved, like: low thermal stability, the high anisotropy of properties of semi products, susceptibility to local deformation and suggested that few of them can be avoided by refinement chemical composition e.g. by reducing Li content below 2% to reduce precipitation on grains boundary.

4. Coatings on to aluminum alloys

The Aluminum alloys applied for elements worked in wear contact. Even with the best possible mechanical properties at the moment, it is limited due to still not enough tribological properties. Additionally, forming Al_2O_3 on the surface effected by high Al reactivity with oxygen cause wear increasing. This phenomenon is generated mainly due to porosity and poor adhesion of Al_2O_3 to the substrate. To overcame existed surface problems the best way is to modify mechanical properties by means of coatings deposition.

From scientific literature analysis, it follows that coatings deposition results in an increased of tribological properties of Al alloys. There are a lot of different surface modification technologies to improve wear resistance [31]: physical vapour deposition (PVD), plasma assisted chemical vapour deposition (PACVD) Gredelj et al. [18], magnetron sputtering, ion implantation Manova et al. [30], pulse laser deposition (PLD) Thomann et al. [53], Major [29], Sicard et al. [48], Pawlowski [38], fluidized bed, Okumiya et al. [37], thermal spraying, Wenzelburger et al. [58,59]. However, few of them seems to be useful due to structure sensitive of aluminum alloys on the temperature of deposition over 473K. From all those technologies, as stated above Wenzelburger et al. [58,59] reported that thermal spraying (Atmospheric Plasma Spraying and High Velocity Oxygen Fuel Spraying) seems to be very perspective method due to flexible processes in terms of component geometry and coatings materials together with low environmental impact during manufacturing. Additionally, during depositions process compressive stress are generated. All those advantages allow easy integration of existing production lines for vehicles' parts subjected to wear or/and contact fatigue.

A special emphasis is put on plasma nitrided of aluminum alloys reported by Telbizova et al. [46], Gredelj et al. [17], Renevier et al. [44], Quast et al. [42]. Applied ion bombardment could involve sputtering of the substrate to remove Al_2O_3 and accelerate reaction of nitride ion with bare substrate. However, due to close pack of aluminum alloys unit cell and from physicochemical point of view it is very difficult to receive relatively deep profile of solid solution of nitride with thin AlN layer on the surface. In contrast to this mainly AlN layer formed and it is diametrically opposed to substrate what could cause discontinuity of mechanical properties. Evans et al. [8] indicated that aluminum nitriding by plasma enhanced chemical vapor deposition method, in a gas phase in a temperature of 473K during 20 minutes cause formation of 20 nm nitride layer. After these time any changes were not observed. Whereas, Gredelj et al. [17] supported in the work that to received ticker AlN layer are indispensable relatively high range of temperature about 673K. Okumiya et al. [37] reported that during his research aluminum surface was modified by ion nitriding and fluidized bed even at 773K – 873K range of temperature. However, it is very probably, that this range of temperature could have bad influence on the aluminum alloys structure. From scientific literature analysis follows that thickness of AlN layer depend on substrate-parameters relationship e.g. from 0,5 μm after 0,5 h in 673K [41,43] to 7 μm of AlN thickness on pure Al after 15 h in 723K, [44]. According to Kent et al. [25] micro-hardness of AlN layer is even up to 1100HV.

5. Conclusion

It seems that to receive ultra light materials with high durability elaborated for components, e.g. in automotive industry mainly to realized light gearbox is needed to take into account the following phenomena:abrasive wear, adhesive wear, fatigue wear and fretting. To overcome such technology difficulties it is considedered necessary to apply interdisciplinary research. The aspects should be taken into consideration: influence and interaction of different elements designed for thermomechanical treatments of Al alloys with full grains and precipitations controlling together with new dispersoid – processing combinations and kind of precipitates (plate-, rod- or lath shaped). It is necessary to apply contact fatigue simulations of substrate-coating system with a functions of different treatments conditions. Additionally, in the light of presented results of research groups it seems that to overcame tribological problems of Al alloys it is necessary to apply Functional Gradient Coatings (FGC) below temperature which could cause destruction of "tailored" structure of the substrate. In our opinion, the point was left without due consideration. For the purpose, further researches are desired on elaborated new (FGC) system, which allows to create a physicochemical transition between Al substrate with outward layer characterized by outstanding tribological properties.

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