GEAR MATERIALS ANALYSIS

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Gears are very common machine components that enable precise transmission of rotational motion and power transmission from shaft to shaft. High demands are placed on the function of gears in operation. They must enable precise, uniform transmission, must not cause noise, often have to transmit large forces, etc. Gears are manufactured from a variety of materials and with different performance specifications depending on the industrial application. Gear materials are required to have high strength, toughness and wear resistance because gears rely on their own design size and material strength to withstand external loads. Material manufacturability is also necessary due to the complex shape of the gear and the high precision requirements of the gear. This study highlights trends in gear materials that are moving towards ultra-high strength, high wear resistance, high temperature resistance, corrosion resistance, and low weight.

KEYWORDS

Gears, material, surface treatment, copper alloys, aluminum alloys, nylon gear, composite materials, hybrid gears

1 INTRODUCTION

Gears are important mechanical components of many machines and equipment, such as industrial machinery, textile machinery, machine tools, electronic equipment, automobiles and many other equipment. Gears can transmit power from one shaft to another, and their main function is to control speed and torque. When two gears mesh, i.e., during gearing, the tooth of one gear fits into the gap of the teeth of the other gear. The meshing teeth of the gears touch each other with their flanks, and the pressure of the teeth on the teeth transmits the circumferential force from the driving gear to the driven gear. With the development of industry, gear materials are developing towards ultra-high strength, high wear resistance, high temperature resistance, corrosion resistance and light weight. There are a number of problems that professionals usually face in the process of manufacturing gears [Duhancik 2024]. Gear wear is the progressive loss of material due to relative movement of the meshing tooth surface. The propagation of gear wear reduces the life of the gear surface, impairs the contact lubrication of the meshing gears, increases friction/noise, and leads to the formation of stress concentrations [Patel 2021, Smeringaiova 2021]. The most common failures include wear, impact, tooth profile deformation, cracks, tooth fractures, peeling of the surface layer, pitting corrosion, etc. (Fig. 1).

The tooth surface should have high resistance to wear, pitting corrosion and the tooth root should have high resistance to fracture. The material of gears is primarily determined by the mechanical stress in a particular application. Commonly used materials include steel, cast iron, aluminum, various plastics, and composites [Murcinkova 2013]. Many industries today face a common problem, which is the need for materials that are strong and flexible, yet lightweight [Malakova 2023]. Composite materials can solve this problem. They can combine the strengths of different materials to achieve better and more efficient results.

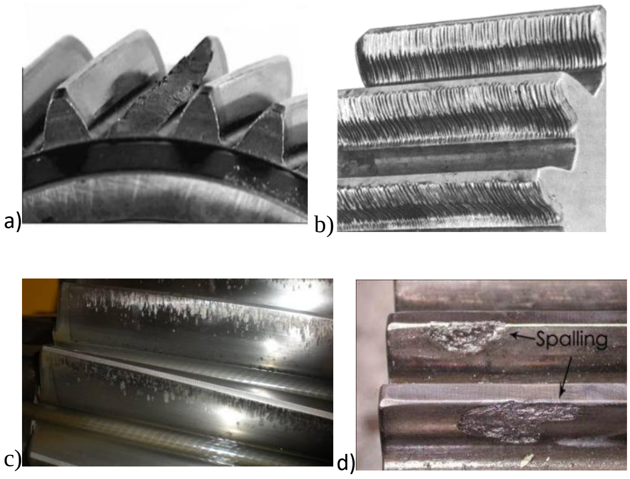

Figure 1. Gear Wear pattern: a) fatigue fracture in the root of the tooth, b) gear wear, c) scuffing, d) spelling

Composite materials are widely used in industries such as aerospace, automotive, construction, and other industrial applications. Composite materials provide adequate strength with reduced weight and have proven to be a better alternative to replace metal gears.

2 GEAR MATERIAL SELECTION

The selection of gear material is complicated and must be related to the specific load and service life required by the application. Recently, a large number of materials and processing techniques have been available to the gear designer. Compatibility with the material, chemical composition, mechanical properties and cost of the mating gear must always be evaluated [Mascenik 2019]. When designing an individual gear or a gear train [Malakova 2022], the choice of material will either be the primary factor on which the gear geometry is based, or the gear performance will dictate the proper material selection. The choice of material affects not only the gearbox's ability to transmit power, but also its resistance to wear and environmental factors. Choosing the right material for gear machining is crucial because it directly affects the performance, life, and efficiency of gear manufacturing.

Figure 2. Choosing the right gearbox materials

When choosing a gearbox material, it is very important to consider the following factors:

a) Strength - gears are subjected to significant loads during operation. The material chosen must have sufficient strength to withstand these forces without deformation or breakage.

b) Wear resistance - gears are in constant contact, which leads to wear over time. Material selection plays an important role in minimizing wear and maximizing the life of the gearbox.

c) Fatigue resistance - gears are subjected to repeated stress cycles. The material must exhibit good fatigue resistance to prevent cracking and eventual failure.

d) Weight - depending on the application, weight can be a deciding factor. Choosing a lightweight material can increase efficiency and reduce the overall weight of the system.
e) Cost - material cost is a significant factor, especially for high-volume production. Striking a balance between performance and cost is essential.
f) Load conditions - the magnitude and type of loading on the gear will affect the maximum strength and wear resistance of the material.
g) Operating environment - exposure to extreme temperatures, corrosive elements or moisture can affect material selection.
h) Noise requirements - Some materials may generate more noise during operation than others.
i) Thermal stability - the material should retain its properties at high operating temperatures.
j) Corrosion resistance - in specific environments, this property is essential to extend the life of the gearbox.
k) Application type - high-speed gears in racing applications require different properties compared to slow-moving gears in a conveyor system.

2.1 Types of gear materials

The gear material and heat treatment have a great influence on the quality and performance of the gear, and it is also necessary to choose the right materials according to the use of the gear. The basic requirements for the properties of gear tooth materials are:

- the surface of the tooth must be hard
- the core of the tooth must be tough.

When designing a gear that will be exposed to a corrosive environment or must be non-magnetic, a copper alloy is usually the best choice (Fig. 3).

Figure 3. Copper alloy gear wheel

The three most common copper alloys used in gearing are brass, phosphor bronze, and aluminum bronze. Brass is an alloy of copper and zinc. Low zinc content maintains a high level of ductility in the brass alloy, while higher zinc concentrations reduce the ductility of the alloy. The copper base of brass alloys contributes to its ease of machining and antimicrobial benefits. Gears typically made from brass alloys are spur gears and pinions that will be used in low-load environments such as instrument drive systems [Monkova 2019, Malakova 2022]. Aluminum bronze is another copper alloy found in gear. This alloy combines copper with aluminum, iron, nickel, and manganese. Aluminum bronze alloys have higher wear resistance than phosphorus bronze alloys and also have excellent corrosion resistance. The addition of iron improves the wear resistance of this alloy. Aluminum and bronze alloys can resist corrosion due to oxidation, exposure to salt water, and exposure to organic acids. The additional wear resistance of these alloys allows the design of gears that can handle significantly greater loads than similarly sized gears made from phosphor bronze alloys.

When gear design requires excellent material strength, iron alloys are the best choice. Steel is an alloy of iron, carbon, and other trace elements. There are four main designations for steel alloys. These are carbon steel, alloy steel, stainless steel, and tool steel. Carbon steel alloys are used for almost all types of gears because they are easy to machine, have good wear resistance, can be hardened, are widely available, and are relatively inexpensive. Stainless steel alloys have a minimum chromium content of 11% and are alloyed with many trace elements including nickel, manganese, silicon, phosphorus, sulfur, and nitrogen. They are divided into ferritic stainless steels, which are magnetic, austenitic stainless steels, which are non-magnetic, martensitic, and precipitation-hardened.
Aluminum alloys are a good alternative to iron alloys in applications that require a high strength-to-weight ratio. Aluminum alloys are typically one-third the weight of steel alloys of the same size.

Figure 4. Gears made from aluminum alloy

A surface treatment known as passivation protects aluminum alloys from oxidation and corrosion. It is similar to rust on steel alloys; however, it coats the surface and protects it from further damage. Aluminum alloys are more expensive than carbon steel but less expensive than stainless steel. However, they are easy to machine, which offsets the increased material cost. Aluminum alloys cannot be used in high temperature environments because they begin to deform at 400°F. Gears made of aluminum alloys include spur gears, helical gears, straight-toothed bevel gears, and spur gears.
Thermoplastics are the best choice for gears where weight is the most important criterion. Gears made of plastics can be machined like metal gears (Fig. 5). However, some thermoplastics are better suited for injection molding. One of the most common injection molded thermoplastics is acetal. This material is also known as polyacetal or polyoxymethylene (POM). The advantages of POM are its dimensional stability over a wide temperature range, low coefficient of friction, and creep resistance. It is an excellent material for wear surfaces because it is self-lubricating, but POM is a poor material for applications subject to shock loads because of its brittleness.

Figure 5. Nylon gear wheel

Figure 6. The material known as unobtainiom

2.2 Most commonly used gear materials

Table 1. Types of Gear Materials

	Carbon Steel		Alloy steel				
	S15CK	S45C	SCM435	SCM440	SNCM439	SCr415	SNC815
Tensile Strength N/mm² More than :	490	690	930	980	980	780	980
Elongation (%) More than:	20	17	15	12	16	15	12
Drawability (%) More than:	50	45	50	45	45	40	45
Hardness HB:	143-265	201-269	269-331	285-325	293-352	217-302	285-388
	Alloy steel		Stainless Steel				
	SNCM220	SNCM420	SUS304	SUS 420J2	SUS 440C	C3604	CAC502
Tensile Strength N/mm² More than:	830	980	520	540	-	335	295
Elongation (%) More than:	17	15	40	12	-	-	10
Drawability (%) More than:	40	40	60	60	-	-	-
Hardness HB:	248-341	293-375	187	217	58HRC	80HV	80

For these types of applications, nylon is a better choice (Fig. 5). Nylon 6/6 is a polyamide that is composed of two monomers with six carbon atoms. Nylon is excellent at absorbing vibrations but becomes dimensionally unstable when exposed to moisture. Nylon is an excellent material for all types of gears, including worm gears, spur gears, spur gears, and bevel gears with straight teeth.

There is one gear material that has not yet been developed. It is an ideal material for all gear designs. This material is known as unobtainium [PairGears 2021] (Fig. 6).

This material is extremely lightweight, has a hardness greater than natural diamond, has a coefficient of friction of 0.001, is dimensionally stable in all environments, does not corrode or o machine, and has a raw material cost of 1 cent per pound. Once invented, it will make all other materials obsolete and greatly improve transmission efficiency.

S45C (carbon steel) - is one of the most commonly used steels, containing a moderate amount of carbon (0.45%). S45C is readily available and is used in the manufacture of spur gears, helical gears, rack gears, bevel gears and worm gears.

SCM440 (Chromium-Molybdenum Alloy Steel) - an alloy steel containing moderate amounts of carbon (0.40%). It also contains chrome / molybdenum. SCM440 has more strength than S45C and is used with thermal-refining or induction-hardening treatment for producing gears.

SCM415 (Chromium-Molybdenum Steel) – is one of the most commonly used low carbon alloy steels (C=0.15%). It has higher strength than S45C or SCM440. The surface hardness should be between 55 and 60 HRC.

SUS303 (stainless steel 18Cr-8Ni) - it is a rust-resistant steel. This authentic stainless steel is basically non-magnetic, most commonly used for gears in applications where rust contamination is undesirable, such as in food-processing machinery. There is a similar stainless steel called SUS304 which has more corrosion resistance than SUS303.

3 COMPOSITE MATERIALS

Composites are modern, but not universal materials. They are always designed for very specific applications with the aim of maximizing the use of their mass. Modern composite materials have a number of advantages over other materials such as steel [Krenicky 2022]. Perhaps the most important is that composites have a much lower weight. They are also resistant to corrosion, are flexible and resistant to overpressure. This means that they require less maintenance and have a longer lifespan than traditional materials.

A composite material is considered to be a material that is composed of at least two or more components that differ in chemical composition - a matrix and a reinforcing component (Fig. 7), which are separated by a distinct boundary, with the resulting material having completely different properties than the two starting components [Rebiei 2007]. The base material, or matrix, has the function of a binder.

Strengthening + matrix = composite component

Figure 7. Composition of the composite material

The function of the matrix is:

• to transfer external loads to the reinforcing component,

• to have a lower melting point than the melting point of the fibers that reinforce them,

• to be tougher than the fibers, to have a lower modulus of elasticity,

• to protect the fibers

The second component, the inserted phase (reinforcement), performs the function of reinforcement, which most often has a reinforcing effect.

The term “reinforcing” (reinforcing, filling) means introduced into the material with the aim of changing its properties (it is not necessarily “reinforcing”).

3.1 Composite materials in gear manufacturing

Composite materials are increasingly recognized as a superior option for gears over metals in a variety of applications, due to several key advantages [Kumar 2021]. Reduced weight, lower cost, better design flexibility, and enhanced corrosion resistance are some of the common reasons for this shift.

Characteristics of the advantages of composite gears:

- Damping effect - For many, the quietness of the entire process is a decisive factor. Composite materials can provide better noise and vibration damping, which reduces the noise of transmission mechanisms. Composite gears allow for greater design optimization to further reduce noise. Complex tooth profiles and integrated damping elements can be manufactured more easily compared to metal gears. Additionally, hybrid metal composite designs can combine the strength of metal with the noise-reducing properties of composites, offering a balanced solution, particularly in automotive, electronic, or precision engineering applications.
- Corrosion resistance - Unlike metal gears, which can be prone to rust and corrosion, composite gears offer inherent corrosion resistance [Kumar 2021]. This makes them particularly suitable for environments exposed to chemicals or moisture, such as marine or industrial applications. This advantage leads to greater reliability and reduces the need for additional protective measures.
- Weight reduction - Composites can be lighter than traditional metal materials, resulting in a reduction in the overall weight of the gears. This is especially important in applications such as automotive gears or aerospace systems, where weight must be minimized to improve performance and efficiency.
- Cost-Effectiveness - Composite gears can also provide a more economical solution. Their manufacturing processes, such as molding or extrusion, are generally faster and less energy-intensive than those used for metal gears. They also eliminate the need for expensive alloys or specialized treatments, leading to overall lower production costs.

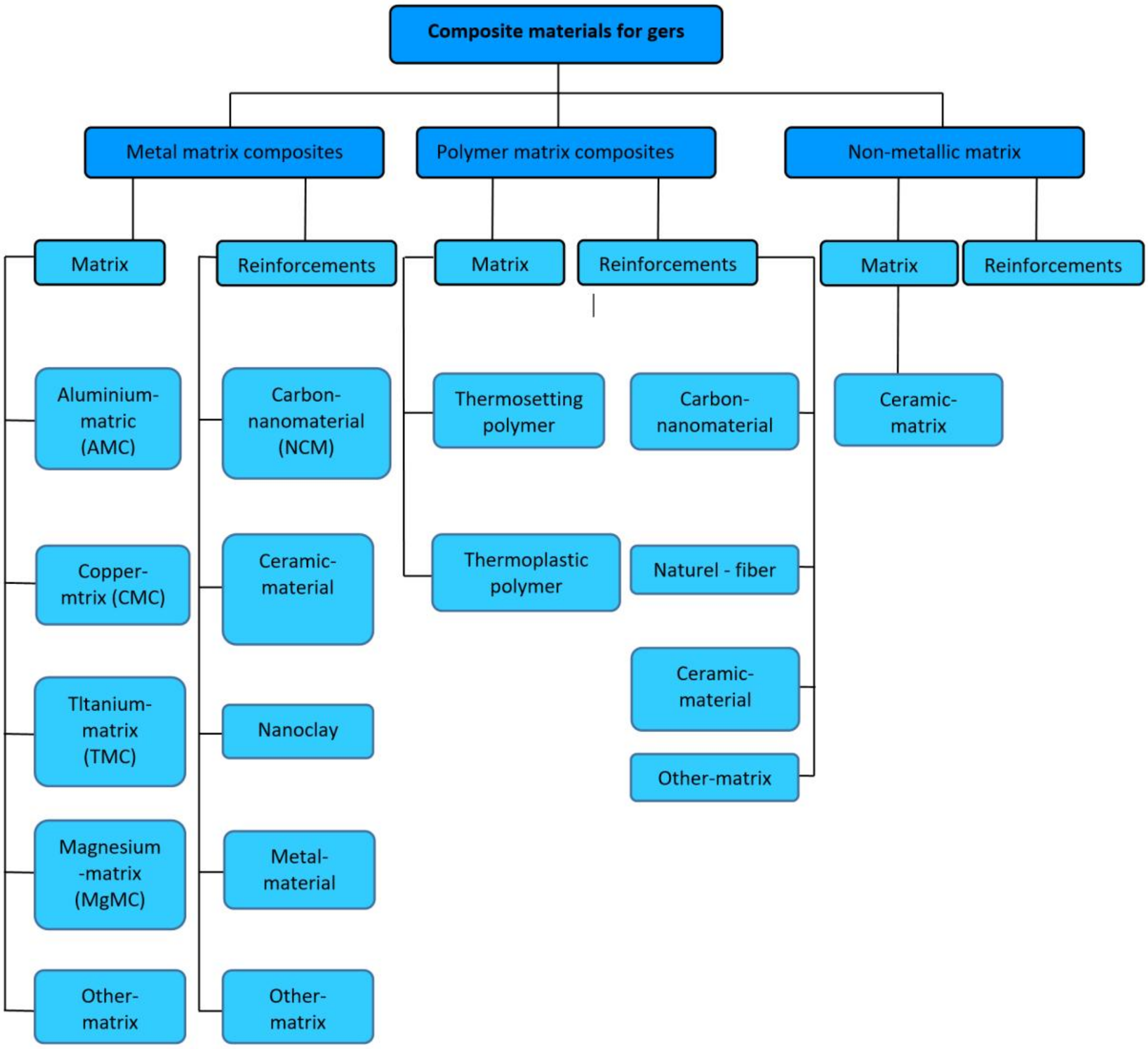

Figure 8. Composite gears overview

Composite gears are divided into three groups based on the type of matrix:

a) polymer matrix composite gears (PMC),

b) metal matrix composite gears (MMC),

(c) non-metallic matrix composite (NMMC) gears.

Among them, PMCs are the most widely used, and the manufacturing process is relatively mature.

PMCs can reduce heat and wear of the contact surface due to their self-lubricating properties.

At the same time, compared with other metals, the viscoelastic properties of polymers can suppress vibration, reduce maintenance, and reduce overall costs [Deng 2013]. Commonly used composite reinforcements include silicon carbide (SiC), tungsten carbide (WC), carbon fiber (CF), glass fiber (GF), nanoclay, graphene, and carbon nanotubes (CNT). Because carbon fiber-reinforced polymer composites have better impact resistance and strength-to-weight ratio, they are expected to replace traditional metal materials in many application areas such as automobiles and aerospace vehicles. Composites reinforced with carbon nanomaterials such as graphene have shown great potential in many industrial applications due to their excellent mechanical properties, thermal properties, and corrosion resistance [Mohan 2018]. In addition, eco-friendly materials such as natural fibers [Shen 2014] are also being continuously applied to composite gears. The matrix materials and reinforcements of commonly used composite gears are shown in Fig. 8.

4 HYBRID GEARS

In recent decades, steel-composite gears have been widely used in aerospace, automotive, and other industrial applications [Jarrett 2023]. With the requirement to improve transmission durability and reduce energy consumption under high load conditions, hybrid metal-composite gears are developed by combining the advantages of metal gears and composite gears. The concept of a hybrid transmission was first introduced in 2012 by a team from NASA Glenn Research Center and the Army Research Laboratory (Fig. 9). The developed hybrid transmission can transmit the same level of torque as an all-metal traditional transmission component.

Figure 9. Prototype hybrid spur gear

Experiments [Handschuh 2023] have reported that hybrid steel-composite gears have sufficient strength to significantly reduce the natural frequency, and their vibration response was sensitive to the load and speed.

A typical hybrid metalo-composite gear consists of the metal teeth, the metal rim, the metal hub, and the composite web (Fig. 10). To ensure that the hybrid gear has sufficient strength and stiffness as a whole, the composite web is fixed with the metal rim and hub in the circumferential direction using slotted fixing structures.

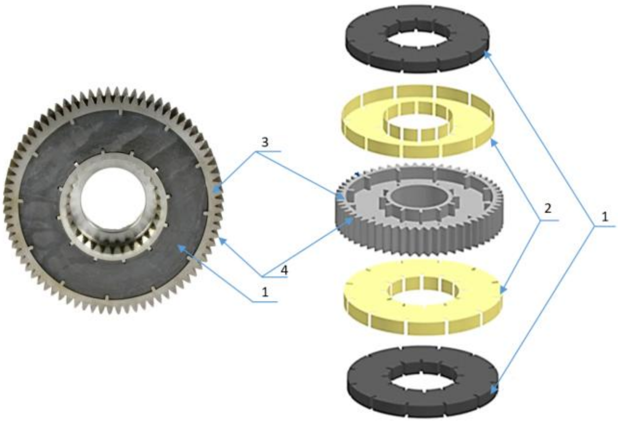

Figure 10. The hybrid gear components: 1 – composite web, 2 – adhesive, 3 – metal rim, 4 – metal teeth

Hybrid steel-composite gears, which combine steel teeth with a composite core, are a rapidly emerging technology for weight reduction [Malakova 2025]. The most common approach to lightening gears is based on material removal, such as making holes in the gear body. Handschuh et al. [Handschuh 2012] proposed weight reduction by proposing a hybrid metal-composite design in which the body is made of triaxial braided composite while the teeth are made of steel. The authors demonstrated a weight reduction of about 20% compared to a metal gear with the same macrogeometry.

This study was conducted to investigate the current status of gear material usage with the requirement to improve gear life.

In the future, the aim of the work will be to show how the use of a composite body affects the behavior of hybrid metal-composite gears during engagement.

5 CONCLUSIONS

The service life of a gear does not always meet the requirements of production practice. Gears are used to transmit power and adjust speed in mechanical devices. They play an important role in products such as automobiles, tractors, machine tools, lifting machinery, etc. The material of the gear has a great influence on the performance of the gear, so it is necessary to choose the gear material wisely. The selection of specific gear materials is mainly determined by the magnitude of the load during gear operation, the speed level and the requirements for gear accuracy. Many gear problems will be solved by composite materials. Composites are composite materials formed by the physical bonding of various simple materials. Composites are modern, but not universal materials. One of the main advantages of composite gears is their significantly lower weight compared to metal gears. Unlike metal gears, which can be prone to rust and corrosion, composite gears offer inherent corrosion resistance. Composite gears offer a compelling alternative to metal gears, especially when noise reduction, weight savings, and design flexibility are critical. While their initial cost may be higher, the long-term benefits in terms of reduced maintenance, efficiency, and performance often outweigh these initial investments. With continued advances in materials, composites are becoming an increasingly attractive option for gear designs, providing the quietness and performance that many industries are seeking.

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KEGA 044TUKE-4/2024 - Application of virtual and augmented reality in education with the aim of innovating design study programs.

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