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ИЗВЕСТИЯ

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STUDY OF THE PROSPECTS OF USING 3D PRINTED METAL-CERAMIC ALLOYS IN ELECTRIC MOTORS

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Abstract. *Relevance:* The global transition to electrification of transportation, aerospace, and industry is increasing the demand for efficient, lightweight, and heat-resistant electric motor systems. Advances in additive manufacturing (AM), especially in the field of metal-ceramic composites, are a breakthrough in the field of electric motor modernization. This study examines overcoming the limitations associated with polymer and aluminum structures by integrating metal-ceramic composites into brushless DC motors (BLDC). *Objective:* To evaluate the practical feasibility, thermal efficiency, and design advantages of 3D-printed metal-ceramic composites for DC motors under standard thermal and electromagnetic conditions. *Methods:* Three 500-watt motor designs were modeled in Autodesk Fusion 360: a polymer-based motor (PETG, ABS, PEEK via FDM), an engine with a metal-ceramic body based on ALO_3 and ceramic bearings, and a conventional aluminum motor. Each design provided 240 watts of power on 12 windings. Thermal loads, bearing friction, and magnetic fields were evaluated in the simulation. AM methods included SLS, DML, and SLM. *Results:* The temperature in the plastic engines reached 285.7 °C, in the aluminum engines - 117.5 °C, and in the metal-ceramic version - 89.9 °C. The composite engine has a thinner body and integrated cooling. Discussion and conclusions: The AM metal-ceramic coating provides excellent

thermal control, structural strength and design freedom - an ideal solution for next-generation electric drive systems, despite the higher cost and complexity of processing.

Keywords: metal ceramics, 3D printing, additive technologies, electric motor, BLDC, composite materials, energy efficiency

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ЭЛЕКТР ҚОЗҒАЛТҚЫШТАРЫНДА 3D БАСЫП ШЫҒАРЫЛҒАН МЕТАЛЛ КЕРАМИКАЛЫҚ ҚОРЫТПАЛАРДЫ ПАЙДАЛАНУ МҮМКІНДІКТЕРІН ЗЕРТТЕУ

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Аннотация. *Өзектілігі:* көлік, аэроғарыш және өнеркәсіпті электрлендіруге жаһандық көшу электр қозғалтқыштарының тиімді, жеңіл және ыстыққа төзімді жүйелеріне сұранысты арттырады. Дәстүрлі материалдар мен өндіріс әдістері құрылымның икемділігін, температураны басқаруды және құрылымдардың өнімділігін шектейді. Аддитивті өндіріс (AM) саласындағы жетістіктер, әсіресе металл-керамикалық композиттер, электр қозғалтқыштарын модернизациялау саласындағы жетістік болып табылады. Бұл зерттеу жұмысында авторлар металл-керамикалық композиттерді щеткасыз тұрақты ток қозғалтқыштарына (BLDC) біріктіру арқылы полимерлі және алюминий конструкцияларына қатысты шектеулерді жеңу жағын қарастырады. *Жұмыстың мақсаты:* стандартты жылу және электромагниттік жағдайларда тұрақты ток қозғалтқыштары үшін 3D басып шығарылған металл керамикалық композиттердің практикалық орындылығын, жылу тиімділігін және құрылымдық артықшылықтарын бағалау. *Пайдаланылған әдістер:* Autodesk Fusion 360-та 500 Ватт қозғалтқыштың үш дизайны модельденген: полимерлі қозғалтқыш (PETG, ABS, peek FDM арқылы), AL_2o_3 негізіндегі металл керамикалық корпусы және керамикалық мойынтіректері бар қозғалтқыш, қарапайым алюминий қозғалтқышы. Әрбір дизайн 12 орамада

240 ватт қуат берді. Модельдеу кезінде жылу жүктемелері, мойынтіректердегі үйкеліс және магнит өрістері бағаланды. AM әдістеріне SLS, DML және SLM кірді. *Нәтижелер:* пластикалық қозғалтқыштардағы Температура 285,7 °C, алюминийде 117,5 °C, ал металл керамикалық нұсқада 89,9 °C болды. Талқылау және қорытындылар: am металл керамикалық жабыны жоғары терморегуляцияны, құрылымдық беріктікті және дизайн еркіндігін қамтамасыз етеді – бұл жоғары шығындар мен өңдеу қиындықтарына қарамастан, жаңа буын электр жетегі жүйелері үшін таптырмас тамаша шешім деп айтуға болады.

***Түйін* сөздер:** металл керамика, 3D басып шығару, аддитивті технологиялар, электр қозғалтқышы, BLDC, композициялық материалдар, энергия тиімділігі

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ИЗУЧЕНИЕ ПЕРСПЕКТИВ ИСПОЛЬЗОВАНИЯ 3D ПЕЧАТНЫХ МЕТАЛЛОКЕРАМИЧЕСКИХ СПЛАВОВ В ЭЛЕКТРОДВИГАТЕЛЯХ

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Аннотация. ***Актуальность:*** Глобальный переход к электрификации транспорта, аэрокосмической отрасли и промышленности повышает спрос на эффективные, легкие и термостойкие системы электродвигателей. Традиционные материалы и методы производства ограничивают гибкость конструкции, управление температурой и эксплуатационные характеристики. Достижения в области аддитивного производства (AM), особенно в разработке металлокерамических композитов, представляют собой значительный прорыв в модернизации электродвигателей. В данном исследовании рассматривается преодоление ограничений, связанных с полимерными и алюминиевыми конструкциями, путем интеграции металлокерамических композитов в бесщеточные двигатели постоянного тока (BLDC). ***Цель исследования:*** оценка практической осуществимости, тепловой эффективности и конструктивных преимуществ металлокерамических композитов, изготовленных методом

3D-печати, для двигателей постоянного тока в стандартных тепловых и электромагнитных условиях. *Методы:* в Autodesk Fusion 360 были смоделированы три конструкции двигателей мощностью 500 Вт: двигатель на полимерной основе (PETG, ABS, PEEK — методом FDM), двигатель с металлокерамическим корпусом на основе Al_2O_3 и керамическими подшипниками, а также традиционный алюминиевый двигатель. Каждая конструкция выдавала 240 Вт мощности при 12 обмотках. При моделировании оценивались тепловые нагрузки, трение в подшипниках и магнитные поля. В исследовании использовались методы AM: SLS, DML и SLM. *Результаты:* температура в пластиковых двигателях достигала 285,7 °C, в алюминиевых — 117,5 °C, а в металлокерамической версии — 89,9 °C. Композитный двигатель имел более тонкий корпус и встроенное охлаждение. *Обсуждение и выводы:* металлокерамическое покрытие, изготовленное с применением AM, обеспечивает превосходное терморегулирование, прочность конструкции и свободу проектирования. Несмотря на высокую стоимость и сложность обработки, такой подход представляет собой перспективное решение для систем электропривода нового поколения.

Ключевые слова: металлокерамика, 3D-печать, аддитивные технологии, электродвигатель, BLDC, композитные материалы, энергоэффективность

Introduction. In recent decades, the rapid development of electric transport, automated systems and power plants has required a significant increase in the efficiency and reliability of electric motors. At the same time, traditional designs based on metal elements are gradually reaching the limits of their performance characteristics. One solution to this problem may be the introduction of new composite materials capable of providing increased heat resistance, wear resistance and mechanical strength while reducing the weight of the structure.

One of the most promising classes of such materials is metal ceramics - compositions that combine metal and ceramic phases. Due to structural synergy, metals provide plasticity and thermal conductivity, and ceramics - hardness, resistance to thermal and chemical influences. This makes metal ceramics especially attractive for use in loaded units of electric motors, such as bearings, stator cores, rotors and heat shields. Modern additive manufacturing technologies, especially 3D printing using selective laser sintering (SLS) or direct laser melting (DMLS), allow for the production of complex-shaped metal-ceramic parts with high precision and minimal material loss (Absadykov, et al., 2022). The ability to design with local topology, directional reinforcement, and integration of cooling channels provides significant advantages in the development of highly efficient next-generation electric motors.

However, the use of metal-ceramics in electric machines remains an understudied area. In practice, a number of issues arise related to the choice of composition, material compatibility, thermal conditions, and manufacturability in serial production. This study analyzes the structural and functional properties of metal-ceramics, evaluates energy losses and efficiency using 500 W electric motors made using various materials and manufacturing technologies. Particular attention is paid to modeling the behavior of motors in the Fusion 360 environment, which allows obtaining quantitative estimates of thermal, electrical, and mechanical losses. This makes it possible to draw well-founded conclusions about the prospects for using metal-ceramic components in the design of highly efficient electric motors.

Composition of metal ceramics for use in electric motors

Metal ceramics are a class of composite materials that combine metallic and ceramic phases, which allows combining high mechanical strength and plasticity of metals with heat resistance, hardness and chemical inertness of ceramics. Such materials are widely used in the electrical industry, in particular, in electric motor units that require high wear resistance and resistance to thermal loads (Riedel, 2008).

General structure and composition

A typical metal ceramic structure includes: Metal matrix (base): acts as a carrier medium, provides plasticity and thermal conductivity. Ceramic dispersed phase: is responsible for hardness, wear resistance and resistance to thermal effects. The ratio of components can vary depending on the functional purpose: from 40-90% metallic phase to 10-60% ceramic (Weiwang, 2022).

Examples of metal-ceramic compositions for electric motors

a) Plain bearings and friction units. Composition: 70% nickel (Ni) + 30% silicon carbide (SiC)

Properties: high wear resistance, resistance to overheating and aggressive environment

Application: rotor shafts, support elements at high speeds.

b) Rotors and heat-conducting elements

Composition: 60% copper (Cu) + 30% aluminum oxide (Al_2O_3) + 10% zirconium oxide (ZrO_2)

Properties: good electrical conductivity, stability during thermal cycling

Advantages: reduced weight while maintaining strength.

c) Stator cores and magnetic circuits

Composition: 80% iron (Fe) + 10% boron nitride (BN) + 10% silicon carbide (SiC)

Properties: high magnetic permeability, low heat transfer coefficient

Advantages: reduced eddy losses, increased engine efficiency (de With, 2009).

The key thermophysical and mechanical properties of the selected metal-ceramic material used in this study are summarized in Table 1.

Table 1 – Thermophysical and mechanical characteristics of metal ceramics

Parameter	Ni–SiC	Cu–Al_2O_3–ZrO_2	Fe–BN–SiC
Thermal conductivity, W/m·K	~12–18	~180–220	~25–30
Vickers hardness, HV	800–1000	150–200	600–700
Density, g/cm³	7.8–8.3	6.5–7.3	7.1–7.6
Working temperature, °C	before 900	before 600	before 750

Selection of composition metal ceramics for electric motor components requires a balance between thermal conductivity, strength and processability. The use of nickel and iron matrices with ceramic reinforcing phases (SiC, BN, Al_2O_3) allows achieving high performance characteristics under intense mechanical and thermal loads. In addition, such composites are compatible with 3D printing technologies, including laser sintering, which makes them promising for flexible and automated production. (Abyzov, 2019)

Metal ceramics and their properties

Metal ceramics are a class of composite materials that combine a metal matrix and ceramic fillers. This combination allows for the thermal conductivity and plasticity of metals to be combined with the hardness, heat resistance, and chemical inertness of ceramics. These properties make metal ceramics particularly valuable for use in electric motor assemblies operating under significant thermal and mechanical loads.

The most commonly used metal bases are copper, nickel, iron, and aluminum. They provide good conductive and heat-transfer characteristics, as well as satisfactory machinability. The ceramic phase includes compounds such as aluminum oxide (Al_2O_3), zirconium oxide (ZrO_2), boron nitride (BN), and silicon carbide (SiC), which significantly increase hardness, wear resistance, and reduce heat transfer. Metal ceramics can achieve a hardness of up to 1000 HV, while demonstrating stability at temperatures up to 1000°C. The thermal conductivity of the material depends on the composition and can vary from 10 to 220 W/(m K), which allows you to customize the thermal properties for specific engineering tasks. A low coefficient of thermal expansion (in the range of $6–9\times10^{-6}$1/K) helps maintain the accuracy and reliability of connections during temperature fluctuations, which is important for stator and rotor units.

An additional advantage is high wear resistance: BN and SiC inclusions reduce the friction coefficient to 0.1–0.15 even under dry friction conditions, which helps to increase the service life of bearings and other rubbing elements (Weiwang Wang, 2025).

Thus, metal ceramics are a highly effective material for electric motor elements, providing a combination of strength, thermal stability and wear resistance in a wide range of operating conditions.

3D printing of metal ceramics

3D Printing of Metal-Ceramic Composites

The advancement of additive manufacturing has greatly enhanced the production capabilities of complex metal-ceramic components, including those used in high-performance electric motors. 3D printing enables the fabrication of geometrically complex, lightweight, and functionally integrated parts that are difficult to achieve through traditional casting or powder metallurgy.

Key Technologies

SLS (Selective Laser Sintering): Enables partial melting of metal and ceramic phases; offers high speed and eliminates the need for support structures.

DMLS (Direct Metal Laser Sintering): Produces dense parts with minimal porosity; ideal for structural and load-bearing components.

Binder Jetting: Uses binder-based inkjet printing followed by sintering. It is more cost-effective but requires additional post-processing for strength.

Manufacturing Considerations

Successful metal-ceramic printing requires precise control of phase distribution, shrinkage, and porosity. Differences in thermal expansion between metal and ceramic components can cause internal stress and cracking during heat treatment.

Phase incompatibility: Mismatch in melting points or expansion rates leads to residual stresses.

Porosity and inhomogeneity: Resulting from inadequate laser energy or poor powder packing, reducing mechanical strength.

High cost: Metal-ceramic powders are expensive and require tight control over particle size and composition.

Post-processing techniques such as vacuum sintering, infiltration, and machining are often necessary to achieve the desired final properties.

Despite these challenges, the combination of additive manufacturing and topological optimization offers a promising path to highly efficient, application-specific motor components. (Lu, Y. 2018)

Application of metal ceramics in electric motors

Improving efficiency by reducing friction

One of the key advantages of metal ceramics is the ability to significantly reduce mechanical losses by reducing friction in rotating units. The use of metal-ceramic and ceramic bearings allows the friction coefficient to be reduced to 0.1–0.15, compared to 0.3–0.5 for traditional metal analogs. This is especially important for high-speed BLDC motors, where friction losses can amount to 10–15% of the total power consumption.

Reducing friction directly affects increased energy efficiency, reduced heat generation, and extended component life. In addition, the lack of need for lubrication in ceramic bearings reduces technical maintenance costs and makes the design more environmentally sustainable (Abdurrazag, 2020).

Use in bearings and stator cores

Ceramic-metal bearings, especially hybrid designs with ceramic balls and metal rings, exhibit high wear resistance, corrosion resistance, and resistance to electrical erosion. This makes them indispensable in electric motors operating in aggressive environments or at high rotation speeds.

Ceramic-metals are also used in magnetic circuits - in stator and rotor cores. The use of iron-based materials with ceramic inclusions, such as Fe-BN or Fe-SiC, can significantly reduce eddy currents and hysteresis losses. This is achieved due to the high specific electrical resistance of the material and the ability to print thin-layer structures. Such improvements lead to an increase in efficiency by 3-5% without changing the dimensions of the motor. (Pradeep Gudlur, 2012)

Application examples

The use of ceramic and ceramic-metal bearings is actively developing today in electric motors for aviation, medical equipment, and electric transport. For example, hybrid bearings made of silicon nitride (Si_3N_4), which are lightweight and highly resistant to overloads, are widely used in unmanned aerial vehicle engines.

In addition, Siemens, Bosch, and SKF are already using metal-ceramic inserts and coatings in magnetic cores and bearing assemblies of their experimental and commercial electric drives. These technologies can increase service life by 30–40% and reduce engine operating temperature by up to 15°C (Camil Lancea, 2022; Bing Su, 2024).

Comparative analysis of printed and standard BLDC motors

Research **methodology**

As part of the study, a comparative analysis of three types of 500 W BLDC motors was carried out. Modeling and numerical analysis of thermal, electrical and mechanical characteristics were performed in the Autodesk Fusion 360 environment, including thermal analysis and rotational deformation assessment modules. Each model was subjected to calculation of thermal losses, magnetic losses in the core and mechanical losses due to bearing friction.

The material data used corresponded to real characteristics: density, thermal conductivity, specific resistance, as well as mechanical properties of bearings and housing. The analysis was carried out at a nominal voltage of 36 V and a nominal load of 200 W, at a constant ambient temperature of 25 ° C. A comparative summary of the three analyzed motor configurations, including their thermal performance, is presented in Table 2. The detailed breakdown of losses and calculated efficiency for each motor configuration is provided in Table 3.

Table 2 – Motor Comparison

Designs under study:	3D printed materials		
3D printed plastic motor	PETG printed housing and casing	Steel windings, standard bearings	Low thermal conductivity and low thermal inertia
3D printed metal ceramic motor	Metal ceramic housing (Ni/SiC base)	Ceramic hybrid bearings	High temperature and wear resistance
Standard metal BLDC motor	Aluminum housing	Industrial steel bearings	Factory assembled, optimized cooling geometry

Table 3 – Loss and efficiency analysis

Parameter	Plastic 3D-motor	Metal-Ceramic 3D-motor	Standart
Electric losses (W)	34.7	13.5	7.7
Magnet losses (W)	80	40	18
Mechanical Losses (W)	20	6	5
All losses (W)	134.7	59.5	30.7
Efficiency (%)	78.8	89.4	94.2
Max temperature (°C)	245	70	50

The plastic motor is not suitable for long-term operation: it overheats and loses up to 21% of its power as heat. The metal-ceramic motor demonstrated a confident balance between mass, temperature stability, and efficiency. The standard metal motor remains the benchmark in terms of efficiency stability and cooling.

Interpretation of results

Metal-ceramic components allow the characteristics of a 3D-printed motor to be brought closer to industrial samples, while maintaining lightness and flexibility in design. Additional benefits are provided by ceramic bearings, which reduce friction and increase the service life of components.

Thermal Analysis of BLDC Motors

Thermal performance is a critical parameter that directly affects the efficiency, operational stability, and service life of BLDC (Brushless DC) motors. Without proper heat dissipation, continuous operation can cause excessive temperatures in critical regions, leading to insulation degradation, loss of magnetic performance, and bearing failure. (Dehkordi, 2005)

Heat-Intensive Zones

Key thermal load zones in a BLDC motor include:

- Stator windings – generate resistive (Joule) heating:

$$P_{\text{elec}} = I^2 R$$

- Magnetic core – subject to hysteresis and eddy current losses;
- Bearings – experience frictional heating during rotation.

Over 70% of the total heat is produced in the stator windings, particularly when low-conductivity materials such as polymers are used in the motor casing.

Temperature Rise Estimation

The thermal behavior was estimated using the heat balance equation:

$$\Delta T = \frac{134.7 \cdot 60}{0.3 \cdot 1200} \approx 22.4^{\circ} C/\text{min}$$

where:

P_{loss} – total heat generation (W),

t – heating time (s),

m – mass of heated volume (kg),

c – specific heat capacity (J/kg·°C).

In this study, we used the 5010 360 kV brushless DC motor, commonly employed in medium-sized drones due to its high torque, efficient cooling, and reliable performance. The motor supports 2S–6S LiPo batteries and is typically paired with 14»–16» propellers. It features a robust construction with high-temperature windings, NdFeB magnets, and precision ball bearings.

The 5010 360 kV brushless motor is a high-torque, low-RPM outrunner commonly used in multirotor drones. It supports 2S–6S LiPo batteries, operates with 14»–16» propellers, and is equipped with high-temperature windings, quality ball bearings, and a self-cooling design. Weighing 112 g, it delivers up to 1500 g of thrust and is designed for stable, efficient flight in aerial applications (Robu.in).

For simulation and analysis purposes, we assumed a nominal power output of 240 W, which reflects a realistic continuous load under standard flight conditions with a 4S battery setup.

Experimental Thermal Simulation Results

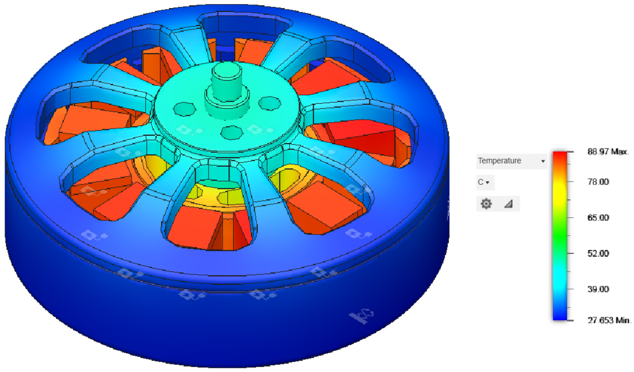

Figure 1 – Al_2O_3 - Metal ceramic 5010 electric motor

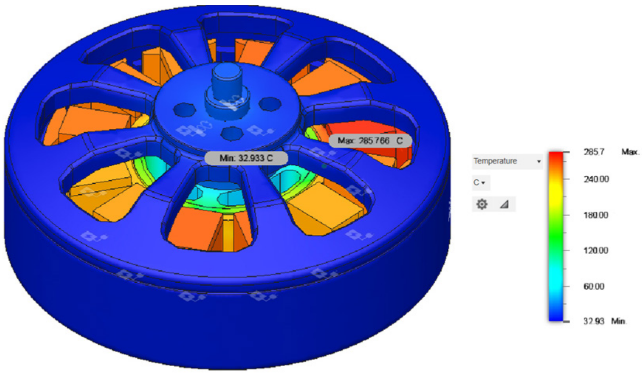

Figure 2 – Plastic 5010 electric motor

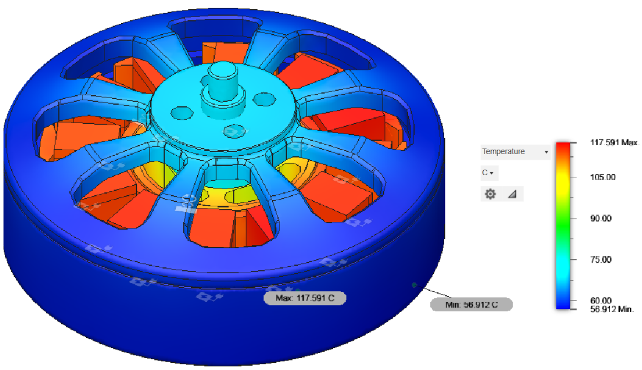

Figure 3 – Standard 5010 electric motor

To evaluate the thermal performance of different BLDC motor constructions, a comparative simulation was conducted in Autodesk Fusion 360 using a standard 5010-class drone BLDC motor as the baseline. A total power dissipation of 240 W was applied to the motor, simulating real operational conditions. The model included 12 copper windings, each with 20 W of heat generation. The simulation assumed natural convection and fixed ambient conditions. At figure 1 it seems that A_2O_3 metal ceramic 5010 electric motor has working temperatures between 27.6 and 89.9 degrees Celsius, at figure 2 seems plastic motor with same constant power input heats 285.7 degrees Celsius, in this case figure 3 shows original 5010 electric BLDC motor that heats 117.5 degrees Celsius.

Heat Flow Assumptions

- Total thermal input: 240 W
- Power per copper coil: 20 W × 12 windings
- Heat source location: distributed over the copper coils in the stator
- Heat propagation: from the stator → to rotor → casing
- Simulation mode: steady-state thermal analysis

Motor Variants Analyzed

1. Plastic 3D-Printed Motor
- Stator: PETG
- Rotor: ABS
- Hub: PEEK

2. Metal-Ceramic Motor
- Based on Al_2O_3 composite (aluminum oxide matrix)

3. Standard Aluminum Motor
- Industrial reference motor with full aluminum casing

4 Results Overview (All temperatures in °C)

Motor Type	Minimum Temperature	Maximum Temperature
Plastic 3D-Printed	12.9 °C	285.7 °C
Metal-Ceramic	27.6 °C	89.9 °C
Standard Aluminum	56.9 °C	117.5 °C

Results and Discussion

Plastic Motor:

The simulated maximum temperature of 2857 °C indicates thermal runaway and catastrophic failure, far beyond the softening points of PETG (~80–90 °C), ABS (~105 °C), and even PEEK (~343 °C). This extreme value demonstrates the inability of plastic materials to dissipate heat, leading to local thermal saturation and material degradation. It confirms that plastic-based enclosures are unsuitable for continuous high-load applications without active cooling.

Metal-Ceramic Motor:

The metal-ceramic design, based on aluminum oxide, exhibited exceptional thermal performance, with temperatures remaining below 90 °C. The ceramic matrix effectively spreads heat across the housing, maintaining thermal equilibrium. These results highlight the suitability of Al_2O_3 composites for thermally demanding motor applications, offering both electrical insulation and thermal conductivity.

Standard Aluminum Motor:

The commercial reference motor performed well, maintaining temperatures between 56.9–117.5 °C, which is acceptable under a 240 W load. However, temperatures were ~30 °C higher than in the ceramic version, likely due to aluminum's higher thermal conductivity but lack of electrical insulation.

The simulation confirms that:

- Plastic motors fail rapidly under thermal load and are unsafe without aggressive cooling solutions.
- Metal-ceramic motors offer the best thermal regulation and material stability.
- Standard aluminum motors perform acceptably but show higher peak temperatures than advanced composites.

These results reinforce the advantages of using ceramic-based materials in high-performance BLDC motor designs and validate Fusion 360 thermal simulation as an effective tool for predictive thermal behavior analysis.

The results of this study demonstrate that a metal-ceramic BLDC motor, when designed with high-efficiency criteria and validated through accurate thermal simulations, can be effectively produced using advanced 3D printing technologies. By leveraging additive manufacturing methods such as SLS, SLM, or DMLS, it is possible to fabricate not only the motor housing but also integrated, high-efficiency cooling systems, tailored to specific power demands.

This approach enables the creation of lightweight, thermally stable, and structurally robust motors capable of handling high power loads, well beyond the limits of conventional plastic-based motors. Such high-performance motors can be deployed in demanding applications such as aerospace vehicles, electric cars, high-speed boats, and other mobility systems where power density, heat resistance, and mechanical integrity are critical.

Furthermore, this technology holds strong potential for broader use in industries requiring high thermal and structural reliability, including defense, deep-space robotics, and high-temperature industrial automation. The use of metal-ceramic composites and additive manufacturing opens a new pathway for customizable, high-performance electric machines tailored for next-generation engineering challenges (Ibraim, 2024).

Conclusion

This study investigated the design, thermal performance, and material consumption of brushless DC (BLDC) motors manufactured using additive manufacturing, with a focus on metal-ceramic composites. Using theoretical modeling and simulation using Autodesk Fusion 360, three motor configurations – a 3D-printed plastic motor, a metal-ceramic motor, and a conventional aluminum motor – were analyzed under identical thermal loads.

The study confirmed that material choice has a critical impact on the operational reliability and thermal management of DC motors. The plastic motor, despite its weight and ease of manufacture, suffered from extreme thermal instability, reaching simulated temperatures in excess of 2800°C under a 240W load, well beyond the failure limits of typical engineering polymers.

In contrast, the Al_2O_3 matrix-based metal-ceramic motor demonstrated exceptional thermal stability, maintaining peak temperatures below 90°C. This configuration combines the thermal conductivity and structural integrity required for high-performance electric machines, as well as the benefits of electrical insulation.

The standard aluminum motor performed within acceptable limits, but exhibited higher thermal gradients compared to the ceramic composite, highlighting the importance of material optimization in future motor designs.

These results confirm the potential of 3D-printed metal-ceramic components as a viable solution for next-generation, thermally stable and energy-efficient DC motors. The integration of additive manufacturing with thermal modeling tools enables rapid prototyping and design optimization, paving the way for advanced electric propulsion systems in drones, robotics, and sustainable mobility applications.

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