Application of auxetic materials in modern car industry and future trends

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ABSTRA
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This research paper is about auxetic materials and their application in modern vehicles. This paper is about the preparation of negative Poisson's ratio foam materials by elucidating the basic principles and classification of auxetic materials in the modern automobile industry, and discusses the latest progress of auxetic materials for hoods and automobile bumpers. Auxetic materials in modern automobiles The unique application of auxetic materials, the basic concept of auxetic materials and their mechanical properties, and the rapid development trend in recent decades. This study adopts the triangular research method and comprehensively uses various methods such as literature review, expert interviews, and pre-standard analysis to achieve a comprehensive evaluation of auxetic materials. Specifically, for each research objective, a corresponding comprehensive evaluation system is constructed using preset standard analysis, so as to deeply discuss the performance, advantages, applications and environmental protection materials of auxetic materials, and evaluate their performance in modern automotive applications. Not only is it of great value to the field of modern automobile industry, but it may also have an impact on material research in other fields. In addition, the research results are scalable, which can provide guidance for the research and development of auxetic materials in the future, and promote the establishment of more systematic research methods and comprehensive evaluation systems. Through this study, a more accurate basis for material selection can be provided, the use of environmentally friendly materials can be promoted, and sustainable development plans can be further formulated

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1 Introduction

This introductory section will first describe the importance of auxetic materials in the automotive industry and outline the research objectives and questions. Subsequently, the research methods used are described, including literature review, expert interviews and pre-standard analysis. At the same time, the research scope and expected contribution are pointed out. With these comprehensive approaches, the aim of this study is to provide a comprehensive assessment of the auxetic materials discussed in each specific context and to provide recommendations for the application and sustainable development of auxetic materials in the automotive industry. Furthermore, the possibility of generalizing the results of this study to the development of auxetic materials by facilitating a more systematic approach to the study of auxetic materials in various fields will be discussed at the end.

1.1Background and motivation

Auxetic material is a metal material that can undergo plastic deformation when stretched and has excellent plasticity and toughness. In automobile manufacturing, tensile expansion materials are widely used, especially in the production of parts such as bodywork and doors. With the continuous research of automobile safety technology and extensive attention to pedestrian safety, pedestrian protection research has become one of the key research contents in the field of automobile safety technology. Tensioned materials have always played an important role in the automotive industry and are used in various components of modern vehicles. Auxetic materials have found widespread use in vehicle bodies and doors. Many of these devices are important to the safety and security of modern vehicles. Despite extensive research, potential challenges in terms of safety and sustainability still stand out. Therefore, in order to understand how modern vehicles, use auxetic devices and how to address the challenges facing the industry, it is necessary to understand the theoretical background of functional auxetic materials and study the manufacturability aspects of auxetic devices. The materials used and the safety of some typical products such as bumpers and doors. When a car has a front-end collision, the bumper system at the very front of the car is the first component to collide with an object. The system absorbs the collision energy through the extrusion deformation of the bumper beam and the energy-absorbing box, and avoids damage to the vehicle body caused by the collision force, thereby ensuring the safety of the occupants in the vehicle. Therefore, in order to reduce casualties in frontal collision accidents, it is necessary to conduct research on automobile auxetic devices.

1.2 Goal of the research

The goal of this research is to build the overall picture about the utilization of auxetic materials in the modern car industry. The discussed viewpoints include the following items:

—The theoretical background and role of stretch-expandable materials

—Theoretical background and function of auxetic materials

— Manufacturability aspects of auxetic materials and products such as bumpers and car hoods

— Sustainability and environmental issues related to auxetic materials.

— Possible commercial auxetic material actually used in modern cars

—Exploring future trends from the perspective of auxetic materials

1.3 Research problem and research questions

The deformation modes and mechanical properties of negative Poisson's ratio structures under tensile, bending, and torsional loads are current research hot spots [1] The production of auxetic materials faces many challenges. These challenges include the development of sustainability, and the environmental impact of auxetic materials. Therefore, this study attempts to address this complex issue by exploring practical and research issues related to the function and application of auxetic materials in modern vehicles, and to provide sustainable solutions for the functions and applications of modern vehicles.

1.3.1Research question

The main research question derived from the research problem is as follows:
"Why are auxetic materials so important for model cars? “The sub-research question is "How stretched and expanded materials affect bumpers and car hoods".

1.4 Research Methods

This thesis will discuss the application of auxetic materials in modern automobiles through a literature search, expert interviews, and preset standards. The tripartite research method will be analyzed by combining literature searches, expert interviews, and pre-set standards. A literature review will be used to discuss the viewpoints related to the goal of this research. In this research, an in-depth reading of the relevant literature will be performed to identify general and specific information related to auxetic materials. In addition, the predefined analytical method to analyze the references will be used to perform a broad assessment of the auxetic materials discussed in this specific context.

1.5 Scope and limitations

The purpose of this paper is to study the application of auxetic materials in modern automobiles, paying particular attention to the bumpers and hoods of automobiles. From the viewpoint of sustainability, this research will be limited to the hazards through fluorine and several low fluorine auxetic materials In addition, the environmentally friendly application of auxetic materials is an important topic in modern automobile manufacturing. In terms of environmental protection, there are some challenges in the application of auxetic materials. For example, the processing of raw materials may cause pollution to the environment, and the disposal and recycling of used auxetic materials also need to be considered as relevant environmental issues.

1.6 Scientific contributions

This thesis is expected to provide new and enriched knowledge for the modern automotive industry and the thesis Includes the explanation of the fundamentals and classes of auxetic materials. This thesis discusses the preparation of auxetic negative Poisson's ratio porous foam materials and the impact energy absorption properties of negative Poisson's ratio materials and structures. Further on, this thesis highlights the results of latest advances of auxetic materials which have been used in automotive hoods and bumper constructions. Finally, in this thesis, it will be examined what are the specific applications of auxetic materials in modern vehicles and their environmental impacts

2 Research methods

This section explains the research methodology utilized in this study, using triangulation. Methods such as literature search, expert interviews, and preset criteria can divide the results into triangulation. In addition, a reliability analysis is described to ensure the credibility of the research results.

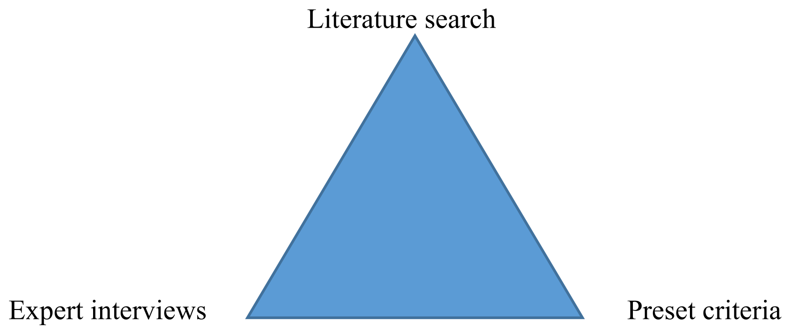


Figure 1 Triangulation

2.1 Triangulation

The purpose of this study is to investigate the application of auxetic materials in modern vehicles, using a triangulation research method (see figure 1), combining expert interview, literature review and pre-standard analysis. The literature review will serve to achieve individual research goals to keep abreast of the latest research advances and achievements in the field of auxetic materials. Expert interview will obtain targeted advice and specific information to support the research in order to gain expertise and experience in a particular field. In this study, expert interview aimed to obtain professional opinions and suggestions on the application and future development direction of auxetic materials in modern vehicles to further support the results of literature review and pre-standard analysis. In addition, a comprehensive evaluation system for auxetic materials in a specific context is constructed using preset standard analysis methods to better understand its application.

2.2 Literature search

Through a literature search, we can understand the research status, methods, and achievements of auxetic materials in this field, to provide a theoretical and practical basis for the research. Literature searches can also help to expand knowledge and gain insight into theory and practice in related fields, Additionally, it can also help to find the source of information and determine the accuracy of the information to a large extent. In this research, the following databases have been used to find relevant and reliable literature references: Scopus, Elsevier, Springer, and Google Scholar.

2.3 Preset standard analysis

The second part of the triangulation is the preset analysis method (see table 1). Specific research objectives are assessed and analyzed against a set of predetermined criteria or indicators. Clarify research goals and problems and formulate corresponding standards or indicators for measurement and evaluation. The criteria used in this study are based on a comprehensive assessment of multiple factors including market direction, public concerns, and expert advice. This is followed by an analysis of relevant references, focusing on technical, social and economic aspects. Finally, information is extracted from relevant references and analyzed and compared using developed questions to make the results more visible and ensure the reliability of the analytical framework.

Table 1. Preset analysis method of the relevant literature

Criteria	Reference [1]	Reference [2]	Reference [3]
What market aspects were discussed?			
Which technological aspects are discussed?			
What economic aspects were discussed?			
What material aspects are discussed?			

2.4 Expert interviews

ln this research, as the third part of the method triangulation, an expert interview [2] has been arranged to discuss the future applications of auxetic materials in the automotive industry and to verify the results of the literature review and the literature analysis. The interviewed expert was an associate professor from Lappeenranta University of Technology who has a lot of experience and knowledge about smart materials. Four main questions have been discussed as follows:

What will be the applications of auxetic materials in automotive parts in the future?
What challenges that auxetic materials may face in the future?
What will be the most likely development directions of auxetic materials in the future?
Do auxetic materials have any advantages in terms of environmental protection?

The author of this thesis has saved the original questions and the registered observations [2] available for possible further needs.

2.5 Reliability analysis

In order to ensure the reliability of this, research the triangulation method will be used. One key aspect will be the use of proper and accurate keywords to search relevant references. Only scientific databases will be used for finding the references. To collect the required information several types of references will be utilized: academic papers, seminars, and report journals. In order to ensure that the references are updated, the message of relatively aged references will be verified from several sources.

3 Literature review on auxetic materials

This thesis contains a comprehensive literature review organized according to five research objectives. Specifically, this review will be divided into the following subsections:

—The theoretical background and role of stretch-expandable materials.

—Manufacturability aspects of auxetic materials and products such as bumpers and car hoods

—Sustainability and environmental issues associated with stretch-expandable materials.

—Possible commercial auxetic materials that Hyundai cars use

—Exploring future trends from the perspective of auxetic materials.

Each subcategory will be carefully developed to address the relevant research question and provide a comprehensive understanding of the current topic.

3.1 Theoretical background and function of auxetic materials

The following sections describe the fundamentals of the auxetic effect and provide an overview of common classes of auxetic materials.

3.1.1 Principle of auxetic effect

Poisson's ratio is a physical quantity that describes the ratio of the absolute value of transverse normal strain to the absolute value of axial normal strain when a material is subjected to unidirectional tension or compression, also known as the transverse deformation coefficient, and is used to reflect the elastic properties of a material deformed in the transverse direction. Generally, most materials have a positive Poisson's ratio, i.e., the material shrinks in the transverse direction in tension and expands in compression. However, there exists a special class of materials that can expand laterally in tension and contract in compression in the elastic range, which is known as the negative Poisson's ratio effect and can also be referred to as the pulling and swelling effect, as shown in Figure 2. This type of material has a higher yield strength, shear modulus and rebound toughness than ordinary materials. Therefore, these materials have significant advantages in energy absorption, crack resistance, vibration isolation and noise reduction.[3]

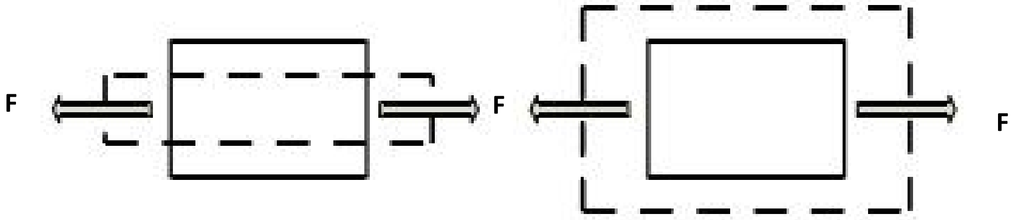


Figure 2 Negative Poisson's ratio effect [3]

Naturally occurring negative Poisson's ratio materials are very rare, so researchers are devoting themselves to the design and research of artificial negative Poisson's ratio materials. The world's first artificial negative Poisson's ratio material was prepared in the laboratory by American Rex. Ordinary polyurethane foam is placed in an aluminum mold, heated, cooled, compressed, and then relaxed. A concave honeycomb structure is obtained [4]. Subsequently, the researchers fabricated negative Poisson's ratio foams using different processes and materials and evaluated their mechanical properties and structures. It was found that the reconstituted foam not only produced a negative Poisson's ratio effect, but also had stronger energy absorption and recovery capabilities than conventional foams [5].

3.1.2 Classification of auxetic materials

In recent years, the research status of negative Poisson's ratio materials is mainly divided into three categories, including: molecular negative Poisson's ratio materials, negative Poisson's ratio composite materials and porous negative Poisson's ratio structures.

3.1.2.1 Molecular Negative Poisson's Ratio Materials

Recent studies have shown that some metallic materials and polymers exhibit negative Poisson's ratio properties, which are caused by their molecular-level structures. These materials include silica crystals, zeolites and certain metallic materials. Examples of molecular negative Poisson's ratio materials include negative Poisson's ratio materials with concave microstructural units at the molecular level [6]. Fishnet-like crystalline films have negative Poisson's ratio properties [7]. Crystalline elements have negative Poisson's ratio properties in the crystal plane direction [8]. Compared with ordinary materials, molecular-level negative Poisson's ratio materials exhibit excellent mechanical properties, making them have broad application prospects in the fields of automobiles, shipbuilding, and national defense.

3.1.2.2 Negative Poisson's Ratio Composite Materials

In an analysis of the fiber compounds, the researchers found that some composites had negative Poisson's ratio properties. In the study of multi-layer fiber materials, it was concluded [9] that negative Poisson's ratio materials can be obtained by stacking different scales. It is generally accepted that there are two main approaches to fabricate composites with negative Poisson's ratio properties. The first is to choose a suitable layup method and introduce highly anisotropic materials into the composite. The second is to add reinforcing fibers with negative Poisson's ratio characteristics, so that when the material is pulled by an external force, the pulling out of the fibers is delayed, causing the material to expand laterally.

3.1.2.3 Porous Negative Poisson's Ratio Structure

Porous negative Poisson's ratio structures are an important branch of negative Poisson's ratio structures and materials, covering foam materials and negative Poisson's ratio structures. Porous materials are usually composed of composite materials, and the porous negative Poisson's ratio structure can be two-dimensional or three-dimensional. At present, three-dimensional foam materials and two-dimensional and three-dimensional structures with negative Poisson's ratio characteristics have been successfully synthesized. The research results [10] show that the main reason for the negative Poisson's ratio of the porous negative Poisson's ratio structure is the structural deformation characteristics of its micro-structural units.

First, researchers [11] successfully prepared a foam material with a concave structure. Its microstructure is shown in Figure 3. The material has an inverted hexagonal structure. When stretched axially, the concave surface of the cell expands outward, and the cell wall expands linearly, thereby increasing the area of the microscopic cell. The materials collide in the vertical and external directions and vice versa, so the structure exhibits a negative Poisson's ratio effect. Negative Poisson's ratio foams exhibit better mechanical properties than conventional foams.

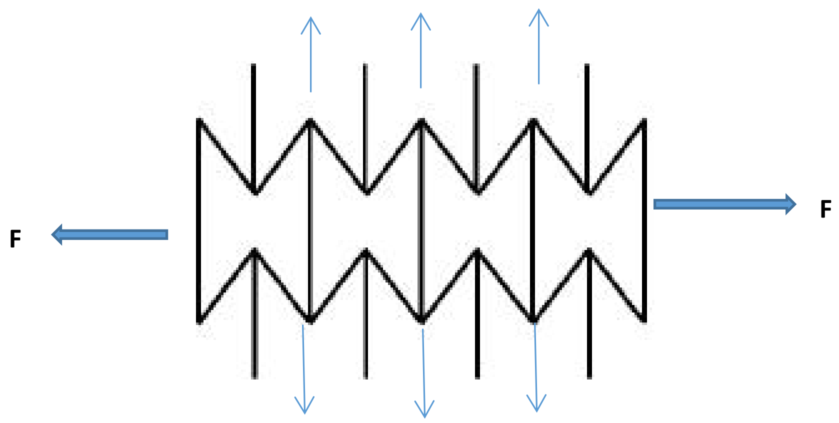


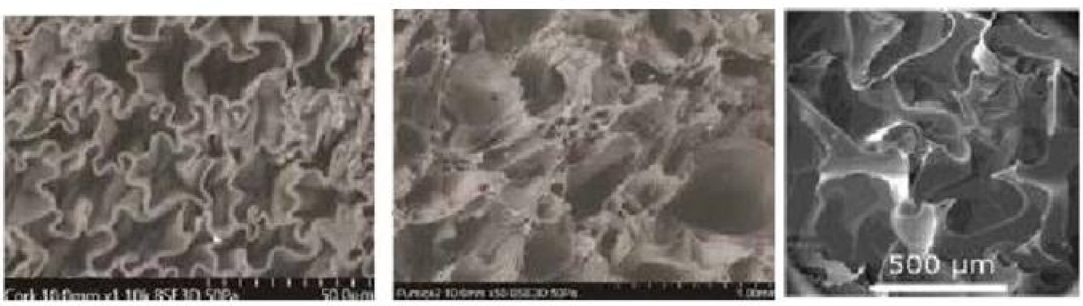
Figure 3 Negative Poisson's ratio foam material with concave structure [11]

3.2 Manufacturability investigation

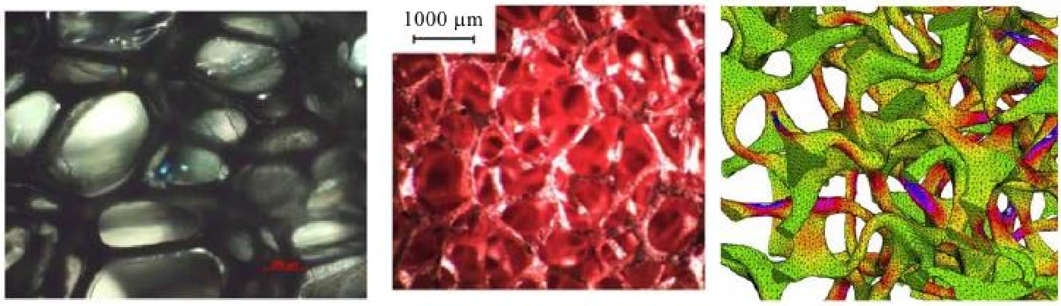
This section provides an overview of the preparation of porous foams and lists some typical negative Poisson's ratio materials and their deformation processes. In addition, the design of automobile bumper systems and crash absorbers for pulling and expanding materials, as well as the application of auxiliary automobile hoods, are highlighted, and the use of internal auxiliary materials is explained in detail.

3.2.1 Preparation of auxetic negative Poisson’s ratio porous foam

A new composite foam with negative Poisson's ratio effect and high specific strength should be prepared. The comprehensive optimization of auxetic effect and high strength has been successfully achieved by selecting the appropriate foam structure. Researchers [12-15] have made new theoretical achievements in the field of foam and composite materials. Their results [12–15] showed that concave honeycombs that do not occur in nature exhibit auxetic properties. If polyurethane foam is put into an aluminum mold, compressed from three directions, then heated to the softening temperature of the material, and then rapidly cooled, relaxed, and solidified, polyurethane with a negative Poisson's ratio is obtained. [16] At the same time, the specially treated porous PTFE resin has auxetic properties. [17-18] Subsequently, several other polymeric and metallic auxetic foams were prepared using similar methods. [19] Since then, scientists have further improved the process, prepared a variety of new auxetic materials, and improved the performance of negative Poisson's ratio polymers and foam materials. [20-24]. A special solvent is used to soften the foam, replacing the heating process in the traditional process, so that the preparation of the auxetic foam becomes a reversible process, that is, the auxetic foam can be reversely processed by "solvent immersion" into an ordinary foam with "memory characteristics". [25] Figure 4 shows some typical negative Poisson's ratio materials and their deformation processes.



(a) Cork microstructure (b) Pumice microstructure (c) Polyurethane foam



d) Shape memory foam (e) NPR copper foam （f)Finite element model of NPR foam material

Figure 4 Different type of Auxetic material structure [12-25]

3.2.2 Negative Poisson's Ratio Automotive Bumper System and Crash-absorbing Box Design

The car's front bumper system plays an important role in the car frontal crash academy. It can protect the life safety of pedestrians and reduce the economic loss of traffic accidents. In the design process of the bumper system, it is necessary to consider the performance and index requirements of different aspects such as structural crash worthiness, collision energy absorption, pedestrian calf protection effect and lightweight design. Through its own continuous plastic deformation, the system absorbs the kinetic energy of the collision under low-speed collision conditions, reduces the impact damage to the lower limbs of pedestrians, and effectively protects the safety of pedestrians. [26-27] took advantage of the synergistic deformation characteristics and energy absorption efficiency of negative Poisson’s ratio structures and proposed a novel bumper structure synergy composed of negative Poisson’s ratio sandwich beam structures and energy-absorbing blocks. Based on pedestrian safety and structural mechanics, the optimal design of the structural energy absorption characteristics of the new negative Poisson's ratio bumper system can be realized.

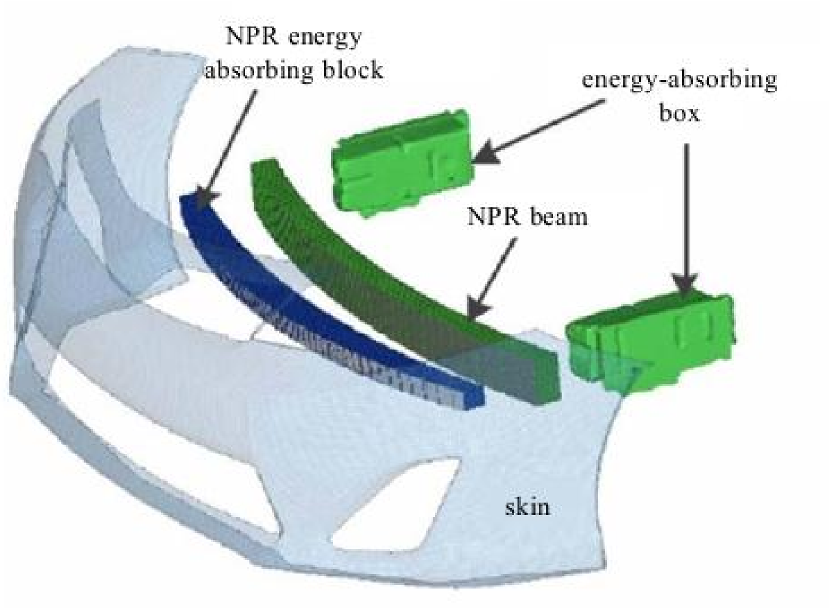


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Figure 5
Negative Poisson's ratio car bumper system including skin, energy absorbing block, cross member [26]

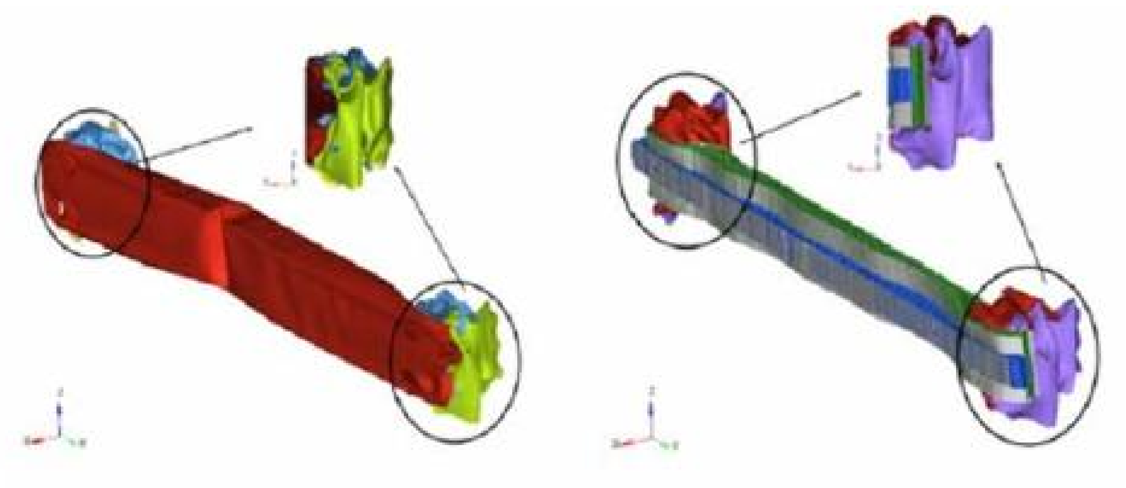

Figure 6
Original rigid bumper system, new type automobile bumper system:
comparison of collision deformation characteristic [27]

3.2.3Auxetic material car hood

Pedestrian protection has always been an important part of automotive safety. Since the risk of head injury and the probability of death are high when pedestrians collide with cars, protecting the head of pedestrians has become the top priority of pedestrian safety protection. In the collision safety design, the vehicle needs the hood to effectively absorb the impact energy of the pedestrian's head, to reduce the injury to the head. In order to improve the effectiveness of the hood in protecting pedestrians' heads in collisions, research institutions and scholars have conducted extensive research and exploration on the structure of the hood and proposed a variety of hood designs based on new materials and new structural technologies. Among them, the new lightweight sandwich material and the hood of the structural core have great application potential. By optimizing the core structure design, the energy absorption capacity and energy absorption efficiency can be improved, and the pedestrian's head can be effectively protected [28]. In order to effectively reduce the collision between the head of the pedestrian and the hood of the car, a new hood sandwich structure was developed [29]. This structure is designed to provide better impact energy absorption performance and reduce head injuries to pedestrians in collisions. Through these innovative designs and research, the performance of automobile hoods in pedestrian collisions can be effectively improved, further improving pedestrian safety

3.3 Sustainability and environmental aspects related to auxetic materials

The application of auxetic materials in automobile manufacturing has been widely recognized, but its production and recycling process also faces sustainability and environmental protection challenges. One of the main concerns is the environmental impact associated with the harmfulness of the metallic elements used in the production of auxetic materials. For example, the production of metal elements such as zinc, aluminum, and magnesium produce large amounts of wastewater and waste gas, which contains harmful chemicals such as fluoride, sulfide, and ammonia. These chemicals are harmful to the environment and human health. In addition, auxetic materials need to be recycled and disposed of, which is also an issue involving environmental protection. If the auxetic material is not properly recycled and disposed of during disposal, it will pollute the environment. Therefore, sustainability and environmental protection measures are required during the production and recycling of auxetic materials to ensure that their application does not negatively affect the environment and human health.

3.3.1 The dangers of fluoride

Fluorides refer to organic or inorganic compounds containing negative fluorine. Excessive fluoride in the human body will cause systemic poisoning, which will not only damage bones and teeth, but also accumulate in various tissues and organs of the human body. Fluoride is widely distributed and mostly exists in natural water bodies. Fluoride has both advantages and disadvantages for human health. Applying it in small doses for a short time can enhance the immune function of the body, while applying fluoride in large doses for a long time will reduce the immune function of the body. Fluorine has a strong irritating and corrosive effect on the eyes, nose, skin, and throat, and can easily cause congestion and inflammation of the mucous membranes of the eyes, nose, and throat. When high concentrations of hydrogen fluoride are inhaled, it can cause bronchitis, pneumonia and other diseases. Patients with skeletal fluorosis will suffer from nerve damage, and fluorine can enter the brain tissue, thereby accumulating in the brain tissue, damaging the brain tissue cells, and producing toxic side effects on the brain tissue cells. Patients with localized fluorosis often present with central nervous system diseases such as emotional instability, headache, and memory loss [30]

3.3.2Advances and challenges in the use of low fluoride pulling and expanding materials

Regarding the harmful effects of low fluorine, it is important to minimize the release of low fluorine in the environment to protect the world's environment and the health of residents. In recent years, several low fluorine auxetic materials have been developed, including: Molecular negative Poisson's ratio materials include some polymers with special microstructures [31] and some crystalline materials such as zeolites [32], silica crystals [33], and some elemental metals [34].

3.3.3 Other environmental concerns

Although high aluminum compound auxetic materials are used to reduce unnecessary fluoride auxetic materials, we need to pay attention that it may also bring new environmental problems. Compounds with high aluminum content may pose potential hazards to human health. Aluminum is a common heavy metal that can enter the human body through food, water, and air. Excessive intake of aluminum may lead to aluminum toxicity, which affects multiple systems and organs, including the nervous system, skeletal system, and lungs. And the negative environmental impact of high-alumina-based auxetic materials may pose additional challenges than the processing and refining steps.[35]

3.4 Commercial Products for Automotive Applications

This section aims to explore the application of auxetic materials in two key components in modern automobile manufacturing: automobile bumpers and automobile hoods. Explore the uses and benefits of these materials by reviewing some of the commercially available products such as auxetic car bonnets for Mercedes Benz, Volvo, Audi, Land Rover bumpers from various manufacturers, etc. to gain a deeper understanding of the properties of auxetic materials and its application in the field of automobile manufacturing.

3.4.1 Mercedes Benz engine hood

Mercedes-Benz recently started using auxetic aluminum in the hoods of its cars to reduce vehicle weight and improve fuel efficiency. Specifically, this aluminum material offers better protection in the hood due to its greater strength and stability at high temperatures. At the same time, the weight of the hood can also be reduced by 20-30%, thereby reducing the overall weight of the car and improving fuel efficiency. In addition to the common advantages of aluminum alloy materials, aluminum auxetic materials also have some unique excellent characteristics, such as low cost of profile extrusion dies, flexible cross-sectional shape design to meet different rigidity requirements, strong air tightness and sound insulation effects, etc. ok wait. At present, the auto parts suitable for the manufacture of aluminum auxetic materials mainly include: front and rear bumpers, door anti-collision beams, energy-absorbing boxes, instrument panel brackets, new energy battery pack shells, guide rails, luggage racks, chassis parts and body parts structural parts wait. [36] Figure 7 shows the hood of a Mercedes-Benz car.

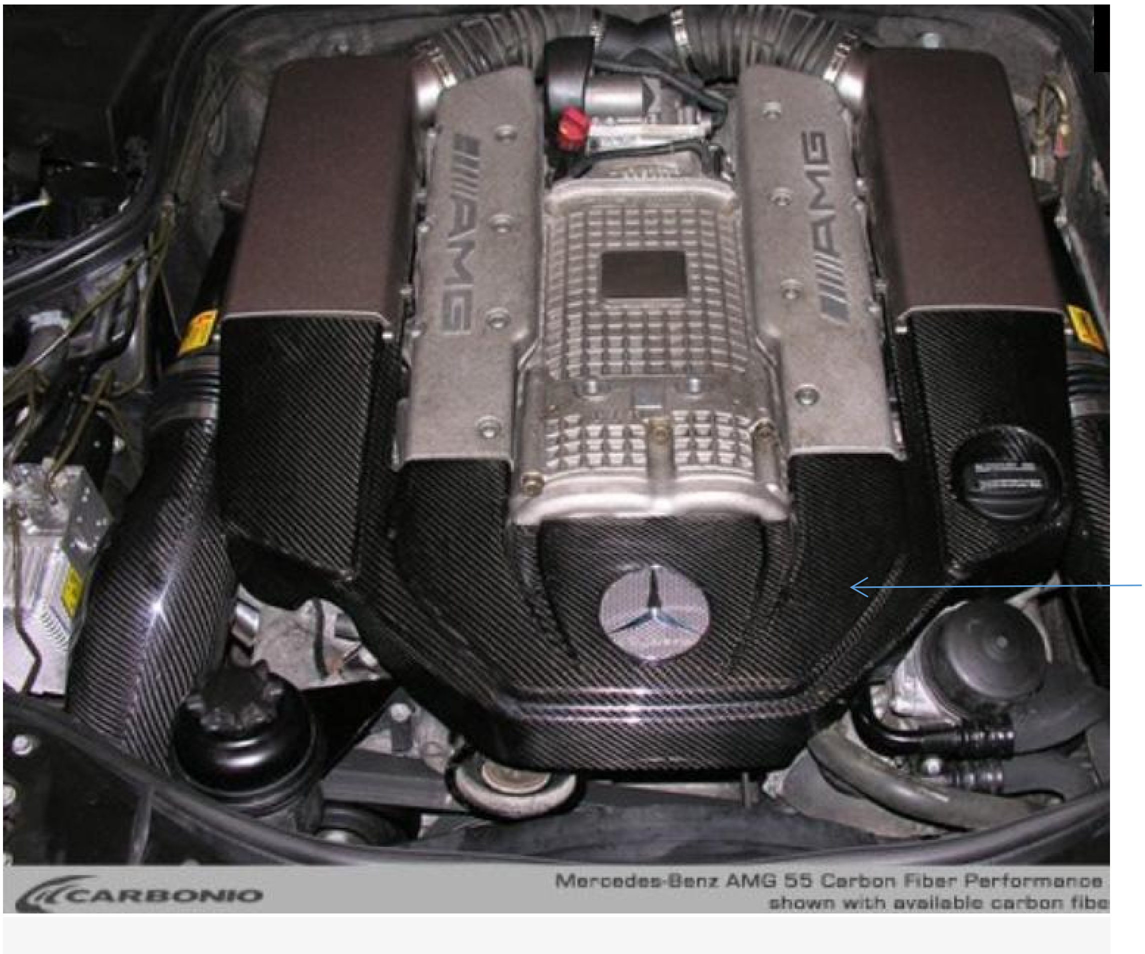

Figure 7 Mercedes Benz engine hood [36]

3.4.2 Audi bumper

As a high-end car manufacturer, Audi has always maintained a leading position in vehicle materials and manufacturing and has continued to innovate in reducing vehicle weight and improving fuel efficiency. Therefore, auxetic materials are used in the manufacture of automobile bumpers. The rear bumper of this material is because the rear bumper of this material has low water absorption and has high impact resistance, rigidity, oil resistance, and cold resistance. Performance, chemical resistance, also has good dimensional stability and aging resistance.

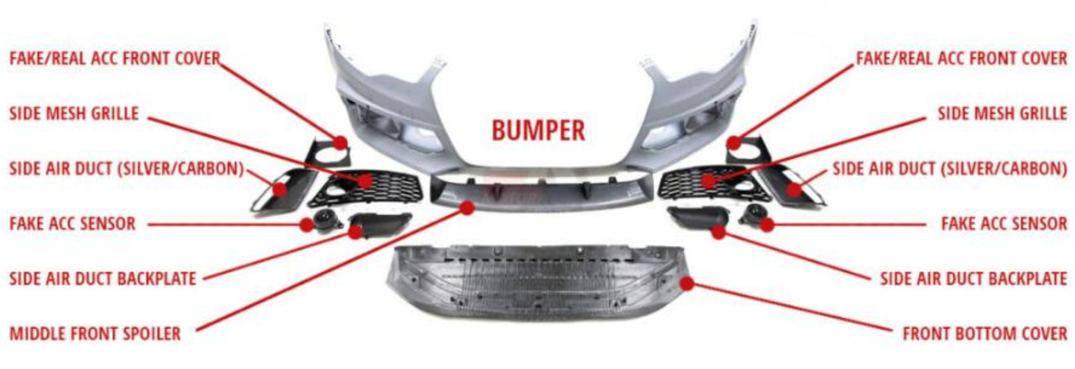

Figure 8 Audi bumper [37]

3.5 Future trends of auxetic materials

This section discusses future trends related to the use of modern auxetic materials in automobiles from a safety and modern energy perspective, focusing on safety and environmental gains as well as possible opportunities and challenges. With the continuous development of the automotive industry, the application of auxetic materials is also expanding. The future trend will pay more attention to the safety and environmental performance of automobiles, regeneration and recyclability, and the use of modern energy.

3.5.1 Recyclability

The metal matrix in the auxetic material can be recycled and reused in production through traditional recycling methods such as smelting and recasting. In addition, the potential of novel recycling technologies such as mechanical reprocessing and advanced thermal treatment methods should also be discussed. [38] See Feasibility of recovering magnesium from end-of-life vehicles. Magnesium and its alloys are widely used materials in modern cars, while auxetic materials often contain metals such as aluminum and magnesium. We need to understand the different methods of recovering magnesium and assess the environmental and economic viability of these methods. Recovery of magnesium from scrapped cars.[39]

3.5.2 Modern energy

The increasing demand for current and sustainable energy sources requires continuous improvement of existing materials to ensure that clean, environmentally friendly and green energy alternatives are available. In this case, the development and improvement of auxetic materials has become an important field for the development of the modern automobile industry.

3.5.3 Further development of auxetic materials

In summary, the negative Poisson’s ratio structure has great application potential in the multi-functionalization of automobile structures, and it is still in the initial stage of industrial application, and the application development is still relatively limited. Further development requires systematic and in-depth research in the following aspects.

(1) The mechanical behavior, deformation mechanism, impact energy absorption characteristics and shock and noise reduction mechanism of various negative Poisson's ratio structures need to be further understood, and relevant theoretical and experimental research is required.

(2) At present, the research on the application of negative Poisson's ratio structure in automotive crash boxes, B-pillars, hoods, seat belts, suspensions, and non-inflatable tires is still fragmentary, and it is difficult to draw comprehensive conclusions. Therefore, it is necessary to focus on Systematic research on the application of negative Poisson's ratio structures to these typical automotive structural parts

(3) It is necessary to carry out systematic research on the large-scale, low-cost manufacturing technology and process optimization of various negative Poisson's ratio structures, such as metal additive manufacturing, composite material forming process, mechanical cutting assembly, casting, welding and other manufacturing processes.

(4) The research work on structural optimization based on negative Poisson's ratio structure in automotive applications is still relatively small, and the optimization methods are relatively limited. It is necessary to combine artificial intelligence, multi-disciplinary multi-objective topology optimization methods, big data and other technologies to carry out in-depth research and further optimize its performance.

3.5.3.1 Negative Poisson's Ratio Material Mechanism

Auxetic materials have unique properties different from ordinary materials and have incomparable advantages in many aspects. First, they exhibit a marked enhancement in mechanical properties. In addition, the properties of auxetic materials affect the transmission of stress waves, thus having potential applications in the manufacture of fasteners or safety belts. [40] The use of auxetic materials in medical applications can greatly reduce the risk of arteriosclerosis. In the manufacture of sandwich panels, [41] negative Poisson's ratio materials can absorb more energy without sagging inwards and causing damage, so the performance of sandwich panels is significantly improved.

In addition, the foam of the auxetic material has special elasticity and sound absorption ability, [42-43] is suitable for making sound insulation materials. A recent study [44] showed that microporous ceramic materials with auxetic effect can be used as support materials for catalytic converters of internal combustion engines.

3.5.3.2 Other challenges of Auxetic Materials

The negative Poisson's ratio structure can be further combined with smart materials (shape memory alloys, shape memory polymers, dielectric elastomers, ferroelectric materials, magnetorheological materials, etc.) to realize the intelligent application of automotive structures. For example: design negative Poisson’s ratio shape memory airless tires to achieve smooth driving on rough roads, design negative Poisson’s ratio adaptive shape memory car rearview mirrors to improve driving safety, design intelligent shape memory negative Poisson’s ratio sunroofs to maintain temperature, etc.

3.6 Mid-summary

Section 3.1 outlines the principle of the auxetic effect and the three Classes of auxetic materials
Negative Poisson's ratio composites, molecular negative Poisson's ratio materials, and porous negative Poisson's ratio structures, including their properties, advantages, and applications.

Section 3.2 discusses techniques related to the use of auxetic materials
An overview of the manufacturing process of auxetic negative Poisson's ratio cellular foams, including Demonstration of some typical negative Poisson's ratio materials and their deformation processes, with emphasis on: Design and availability of negative Poisson's ratio automotive bumper systems and crash absorbers and automobiles Manufacturability studies of auxetic material hoods.

Section 3.3 discusses the sustainability and environmental aspects related to auxetic materials mainly including
The hazards of fluoride and several low-fluorine auxetic materials, etc., use auxetic materials with high aluminum content to reduce reliance on fluoride auxetic materials Use molecular negative Poisson's ratio materials Zeolite, silica crystals and some elemental metals and Alumina-based auxetic materials have a negative impact on the environment and can pose more challenges than processing and refining steps.

Section 3.4 discusses how to use auxetic materials
Discuss the application of auxetic materials in two key components of modern car manufacturing: car bumpers and car hoods, such as Mercedes-Benz, Volvo, Audi, Land Rover bumpers and other manufacturers' auxetic car hoods etc. and their features and benefits.

Section 3.5 discusses future trends related to the use of
Recycle and reuse in production through traditional recycling methods such as smelting and recasting and check the feasibility of recovering magnesium from scrapped vehicles. The further development direction of auxetic materials includes: combined with artificial intelligence, the key systematic research on the negative Poisson's ratio structure in The application of these typical automotive structural parts, systematic research on the large-scale, low-cost manufacturing technology and process optimization of various negative Poisson's ratio structures, the mechanical behavior, deformation mechanism, and impact energy absorption characteristics of various negative Poisson's ratio structures And further understanding of the shock and noise reduction mechanism, etc.

4 RESULTS

The results of this study will contain three aspects, namely scientific contribution, specific application and generalizable results, each of which will be evaluated. The literature review has played a key role in building the overall application of auxetic materials in the modern automotive industry. In addition, the research objective employs pre-specified standard analyzes to construct a comprehensive evaluation environment for each specifically discussed auxetic material. The application prospects of auxetic material structures in the automotive industry are prospected through expert interviews. Results involving scientific contributions and specific applications build on observations based on literature review and analysis as well as aspects selected from expert interviews.

4.1 Results of literature review

The results of the literature review raise several important issues for discussion. The literature first discusses the concept of negative Poisson's ratio, negative Poisson's ratio foam materials and composite materials, typical negative Poisson's ratio structure design methods, and impact energy absorption characteristics of negative Poisson's ratio structures from the literature search. Materials and structures, mechanical design methods and performance advantages. Secondly, through the application of auxetic material structures in typical automotive structural parts, the great advantages of auxetic material structure design are demonstrated. Auxetic Materials, Manufacturability Studies and Discussions for Automotive Design and Bumper Systems and Auxetic Materials for Automotive Hoods discuss sustainability and environmental aspects related to auxetic materials, mainly including the hazards of fluorine and several low fluorine auxetics. Materials, selection of high fluorine auxetic materials aluminum content and use of auxetic materials.

4.2 Observations based on the preset analysis tool

The detailed results and observations based on the preset analysis tool are collected and presented in appendixes 1…4. The main contribution is compressed as follows.
The modern automotive industry recommends trigonometry. Methods such as literature search, expert interviews, and pre-set criteria used the information presented in this study for the following measures:
-Assessment Literature Search Auxetic Material Safety Application Assessment: Automakers can use this information to determine which car parts could use auxetic materials to improve safety. For example, using auxetic materials to make parts such as automobile bumpers and body frames can improve the stability of the vehicle and further improve the safety performance of the vehicle.
-Make better decisions on a material selection with preset criteria: Use of auxetic materials with high aluminum content to reduce reliance on fluorine-containing auxetic materials Use of molecularly negative Poisson's ratio materials Zeolites, silica crystals, and some elemental metals
-Assessing the literature search to reduce the environmental impact of The evaluation literature search mainly includes the hazards of fluorine and several low-fluorine auxetic materials. The automotive industry can reduce environmental pollution by improving auxetic materials
-Assessing Literature Search Towards Sustainability: Evaluation literature search Feasibility of recovering magnesium from end-of-life vehicles, tested by recycling in production for traditional recovery methods such as smelting, and recasting. The automotive industry can leverage these for sustainable vehicle production

4.3 Results of the expert interview

ln this research, as the third part of the method triangulation, an expert interview [2] has been arranged to discuss the future applications of auxetic materials in the automotive industry and to verify the results of the literature review and the literature analysis. The interviewed expert was an associate professor from Lappeenranta University of Technology who has a lot of experience and knowledge about smart materials. Four main questions have been discussed as follows:

First, the discussions focused on the applications of auxetic materials in automotive parts for the future. The expert’s answer mainly included two aspects: noise reduction equipment and safety devices.

Noise reduction equipment: In the future, auxetic materials are expected to be widely used in interior car door panels to reduce the impact of noise on people's daily lives. By using auxetic materials in the interior door panels, the transmission of noise can be effectively isolated, and a quieter driving environment can be provided.

Safety device: Many auxetic materials have an excellent impact absorption ability, which plays an important role in reducing the impact force and the injury to the occupant in a collision accident. In the future, auxetic materials are expected to be applied to safety devices such as automobile dashboards. By absorbing and dispersing the impact force during a collision, it can reduce the damage to the occupant's head and body, improve driving safety, and reduce the risk of serious injury.

The second question discussed the following challenges that auxetic materials may face:

Polymers: Polymer materials may release harmful chemicals during their manufacturing process and use, posing potential risks to the environment and human health. Therefore, when developing auxetic materials, it is necessary to pay attention to the toxicity of the materials and the release of pollutants and takes corresponding measures to reduce the content and release of harmful substances to protect the environment and human health.

Loss of expansion protection: In practical applications, auxetic materials may face functional failure if they cannot expand properly or provide the desired protection. Therefore, future research needs to address this challenge to ensure that auxetic materials perform well and provide the desired protective properties under a wide range of conditions. Typical problems are faced during the joining stages of auxetic materials.

The third question was about the development direction of auxetic materials in the future, including:

Chemistry: Future research will focus on developing auxetic materials with specific functionalities. Researchers will explore new material combinations and chemical structures. In addition, future developments will also focus on the manufacturing techniques and processes of auxetic materials, seeking more efficient and scalable preparation methods. It might be possible to integrate several smart material properties in the same material bulk.

Artificial intelligence: Artificial intelligence technology is increasingly used in the automotive industry, and fields related to auxetic materials are no exception.

The last question was whether auxetic materials have advantages in terms of environmental protection:

The issues of recycling technologies were discussed: auxetic materials are often recyclable, which means that in many cases the waste generated after the use can be recycled and reused however, the recyclability depends a lot on the chemical composition of the auxetic material.

4.4 Generalizable results

The widespread application of auxetic materials in modern automobile manufacturing is sustainable and has great potential for promotion. With the continuous development of technology, more and more auto parts will use auxetic materials to replace traditional materials, which will promote the development of the auto manufacturing industry in a more environmentally friendly and sustainable direction. In addition, with the global emphasis on environmental protection and the strengthening of automobile emission standards, the use of auxetic materials will become a trend in the automobile manufacturing industry, which will help reduce the negative impact on the environment. And in the future, combining artificial intelligence, there will be many possibilities. Therefore, the results obtained from this study may be used in future research on other materials.

5 Discussion

The discussion mainly includes the following aspects, comparison and connection, objectivity, reliability, evaluation of results, main findings, novelty value of results, generalization and utilization of results.

5.1 Compare and connect

The current study appears to provide a more comprehensive understanding of the fundamentals and classification of auxetic materials, negative Poisson's ratio composites, molecular negative Poisson's ratio materials, and porous negative Poisson's ratio structures, including their properties, advantages, and applications. As well as information about the sustainability and environmental aspects of auxetic materials, as well as environmentally friendly alternatives, which may be new ideas. Furthermore, the thesis focuses on different research directions and results in terms of sustainability and the environment, showing that the research on modern vehicle auxiliary materials is completely different from previous research. The combination of artificial intelligence and materials in various fields mentioned in the framework of the paper may also provide inspiration for future research on this topic. Overall, the current research paper extends previous research on auxetic materials for modern vehicles.

5.2 Objectivity of auxetic materials

This study used a triangulation approach that organically combined a literature review, expert interviews, and pre-criteria analysis to obtain comprehensive information on the application of auxiliary materials in modern automobiles. The literature review served as the main source of information base and provided extensive and reliable background knowledge for the study. Expert interviews were conducted at different stages of the study to obtain general and specific information and to ensure the integrity and depth of the study objectives. A pre-criteria analysis was used to validate the research questions and to improve the accuracy and credibility of the findings. Through this integrated approach, this study obtained comprehensive and reliable information on the application of auxiliary materials in modern automobiles.

5.3 Reliability of auxetic materials

Current research has been solid. First, through expert interviews, four main questions were raised and clear answers were obtained. Second, reliable scientific databases were used to screen sources. Finally, classify by content to facilitate the distinction of required information, such as academic papers, seminar content, report periodicals, etc., so that the information obtained is accurate. And in order to ensure that the references are updated, they are classified according to the order of publication time to ensure that the information obtained is accurate and reliable. Use academic search engines, databases, academic journals, conference proceedings, professional books and other resources to obtain relevant information

5.4 Assessment of the results

The scientific contribution of this paper presents new perspectives. Papers cover a wide range of research areas, including porous negative Poisson's ratio structures in modern automobiles, negative Poisson's ratio vehicle design, and bumper systems. This article details the fundamentals and classification of these materials, providing information on their properties, advantages, and applications, including auxetic materials, negative Poisson's ratio composites, and molecular negative Poisson's ratio materials. Furthermore, future trends and areas for improvement are suggested by evaluating different applications of auxetic materials in modern vehicles. These discussions may also lead to more sustainable options for car production. The information and conclusions provided by the research also have an important guiding role for research in other fields and can provide more systematic research methods for these fields. In summary, this research brings new perspectives to the field of modern automobile industry and may have a profound impact on the future research of artificial intelligence materials.

5.5 Key findings

The study yielded several key findings. First, the development of auxetic materials plays a vital role in modern automobiles, especially the manufacturability study of auxetic materials for automotive hood bumpers. The second point is the sustainable development of auxetic materials. The use of fluoride in auxetic materials has negative environmental impacts and has been replaced by auxetic alternatives with high aluminum content. The third point, Fabrication of Auxetic Negative Poisson's Ratio Foam, summarizes the fabrication process of auxetic negative Poisson's ratio foam, including demonstrations of some typical negative Poisson's ratio materials and their deformation processes. The fourth point is the commercialization of auxetic materials. The application in modern automobiles, the commercial value of auxetic materials and its future development trend, and finally the possible future development direction of auxetic materials combined with artificial intelligence.

5.6 The novelty value of the results

This research thesis presents new results in auxetic materials for modern vehicles. The research objects of this thesis are auxetic materials and their relationship with negative Poisson's ratio composite materials, molecular negative Poisson's ratio materials, and porous negative Poisson's ratio structures, and their properties and applications are introduced in detail. In addition, the research paper also discusses how to prepare auxetic negative Poisson's ratio porous foams and the relationship between auxetic materials and the environment. These contents are unprecedented and provide new insights and potential directions for future research in the modern automotive industry. In addition, the application of auxetic materials in automotive design and bumper systems is investigated and methods for improving these applications are provided. The novelty of these results is that they provide new ideas and solutions, opening up new possibilities for the development of the modern automotive industry. At the same time, it also proposes how to use more reasonable and environmentally friendly methods, which also provides new ideas and solutions for the sustainable practice of automobile production.

5.7 Generalization and utilization of the results

According to literature review and expert interviews, auxetic materials can be widely used in many fields such as modern automobile industry, medical equipment, construction, and aerospace. Therefore, the research results of the proposed auxetic materials have broad application prospects. Promote the use of value. In addition, the paper also mentioned the development direction and improvement direction of auxetic materials in the future, such as combining auxetic materials with other materials to improve their performance, exploring more methods for preparing auxetic materials, etc. These directions can provide more opportunities.

5.8 Topics for future research

The negative Poisson's ratio structure can be further combined with smart materials (shape memory alloys, shape memory polymers, dielectric elastomers, ferroelectric materials, magnetorheological materials, etc.) to realize the intelligent application of automobile structures, such as designing Negative Poisson's ratio shape memory air-free tires to achieve smooth driving on rough roads, negative Poisson's ratio adaptive shape memory car rearview mirrors to improve driving safety, intelligent shape memory negative Poisson's ratio sunroofs to maintain a constant temperature inside the car, etc. .

6 Summary

This research paper deals with auxetic materials used in modern vehicles and their application in automotive design. This paper adopts the triangular research method, combined with literature review, expert interviews and pre-standard analysis, to obtain comprehensive information and verification issues, which improves the accuracy and credibility of the research results. Because it provides the properties, advantages and applications of auxetic materials and negative Poisson's ratio composites, molecular negative Poisson's ratio materials and porous negative Poisson's ratio structures in modern vehicles. Future trends and areas of future improvement for auxetic materials are described, and how they can be used more wisely and to the benefit of the environment is discussed, as well as the implications of these for more sustainable practices in automotive production. At the same time, the proposed research may have a significant impact on research in other fields and provide them with a more systematic approach to study various fields. Future research may focus on the preparation process of auxetic negative Poisson's ratio porous foams, and the relationship between auxetic materials and environmental factors. At the same time, this study can further explore new applications of auxetic materials in automotive design, and explore the application of auxetic materials in other fields

7 References

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Appendix 1 Pre-set criteria: "Functionality of different types of piezoelectric materials"

Criteria	Negative Poisson's Ratio Polymers and Carbon Nanocomposites:" (2020)	Negative Poisson's ratio properties of porous materials (2021)	Negative Poisson's ratio in modern functional materials" (2017)
What material aspects are discussed?	Negative Poisson's Ratio Composite Materials	Porous Negative Poisson's Ratio Structure	Molecular Negative Poisson's Ratio Materials
What market aspects were discussed?	High compressibility, High tensile stiffness, High shear stiffness	Shock absorption, sound insulation, filtration, energy storage, etc.	Nanowires, nanosheets, nanospheres, etc.
Which technological aspects are discussed?	Micro-nano preparation method, Material engineering Assembly method, etc.	Sol-gel method 3D printing method	Nanofabrication technology self-assembly technology
What economic aspects were discussed?	Cost-effective	Low cost	n/a

[1] Negative Poisson's Ratio Polymeric and Carbonaceous Nanocomposites: A Review" (2020), by A. Tounsi, et al. This review article provides an overview of the recent progress in the development of negative Poisson's ratio polymeric and carbonaceous nanocomposites. The authors discuss the various methods used to prepare these materials and their potential applications in fields such as energy absorption, aerospace, and biomedical engineering.
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[3] Negative Poisson's ratio in modern functional materials: A review" (2017) by Wang et althea research history and recent progress of molecular negative Poisson's ratio materials, and their preparation methods and performance characteristics are discussed.

Appendix 2 Preset Standard: "Manufacturability of Auxetic Automotive Hoods and Bumpers with Aspects of Manufacturability Related to Auxetic Materials"

Criteria	Study on the structure optimization of automobile engine hood based on multi-objective optimization (2019)	Study on the Forming Process of Magnesium Alloy Front Bumper. Journal of Materials Engineering and Performance (2020)	Investigation on Hot Stamping Process and Mechanical Property of High Strength Steel Car Bumper (2020)

What material aspects are discussed?	Car hood	Bumper	Bumper
What market aspects were discussed?	Effectively reduce body weight and improve vehicle performance and fuel economy	Good impact resistance, Plastic deformation capacity	Energy absorption capacity
Which technological aspects are discussed?	Processes such as cold stamping or hot forming	Inverse stretch forming technology	Superplastic forming technology, etc.
What economic aspects were discussed?	Reduce material waste and environmental pollution	Improve performance and reduce manufacturing cost of auxetic material bumper	n/a

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Appendix 3 Preset Standard: "Detrimental Effects of Low Fluorine Auxetic and High Fluorine Auxetic Materials"

Criteria	Highly stretchable poly (vinylidene fluoride-hexafluoropropylene copolymer)-based materials for flexible electronics (2019)	Recent advances in fluorinated elastomers for high-performance applications. (2019)	ffect of aluminum content on the microstructure and mechanical properties of zinc-aluminum alloys for automotive applications. (2016)

What material aspects are discussed?	PVDF PTFE	PFA	PFEA
What market aspects were discussed?	Lubricating materials, electrical insulation materials, high temperature sealing materials	High temperature stability, chemical resistance	Tensile properties, lower density
Which technological aspects are discussed?	Chemical stability, heat resistance, weather resistance and mechanical properties	n/a	N/a
What economic aspects were discussed?	Reduce environmental pollution	Chemical resistance, low surface energy	Improve fuel economy

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Appendix 4 Preset Standard: "Products for Automotive Commercial Auxetic Applications"

Criteria	Audi bumper (2023)	Mercedes Babos Car hood (2023)	Land Rover Range Rover (2022)
What material aspects are discussed?	bumper	Car hood	Car hood

What market aspects were discussed?	Impact resistance	increase the strength of the material,	Improve plasticity and corrosion resistance of materials
Which technological aspects are discussed?	n/a	n/a	n/a
What economic aspects were discussed?	Shorten the production cycle, improve the efficiency and output of automobile manufacturing	Improve fuel economy	Improve fuel economy