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To cite this article: W D Abdul Jalil 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **737** 012078

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IOP Conf. Series: Materials Science and Engineering **737** (2020) 012078 doi:10.1088/1757-899X/737/1/012078

Smart textiles for the architectural façade

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Abstract. Historically, the availability of new materials inspires designers and architects with new potential solutions. Recently, architectural applications have more concerns about sustainable requirements, which are combined with the development of nanotechnology. The availability of nanomaterials and nano-devices offer the possibility to produce smart textiles. However, smart textiles witness a commercial production and increasing application for the contemporary architectural façades. The availability of nanomaterials adds smartness to the textiles by the use of a coating, like self-healing, antimicrobial, anti-fouling, self-thermos regulating, etc. Other nanomaterials are used like conductive ink, thermos-chromic inks, conductive polymers, conductive threads, shape memory materials, piezoelectric materials, and ceramic materials to produce nano-devices that add smartness to the textiles. The paper aims to detect the inquiry about the multi-functional properties of smart textiles for the architectural façade. The methodology follows a descriptive method to study the use of smart textiles, relying on the data collected from previous theoretical literature. A chosen case study has been described briefly and analysed to indicate the multi-functional properties of smart textile used. As a conclusion, smart textiles are used according to the purpose that is proposed by the designer. They are used to fulfil aesthetic, structural and environmental functions. The most effective property is the potentiality that has been available to create interactive and creative shapes and patterns for the architectural façade with additional sustainable multi-functions.

1. Introduction

Using textile in architecture isn't new. However, textiles have many good properties like the clear-span design, lightweight, flexible, quick to install, easy to relocate and easy to transport. They have low weight/strength ratio. They need a low maintenance and less labor. [1] In recent years, many innovations of nanotechnology in the industry of textile make them smart and active. While traditional materials already have multi-functions, nanomaterials and nano-sensors add a new version for the 21st century textiles to be used for the architectural façades. Smart textiles according to their types, introduce additional multi-functions like thermal and sound insulating, ventilation controlling, sunlight controlling, air filtering, solar energy collecting, wind energy collecting or motion energy collecting. [2] So smart textiles witness a spared using in contemporary architecture. Recently, many textiles are commercially available for architects and designers to be used to fulfil the functional and aesthetic requirements of architecture and design.

2. Nanotechnology

It is a revolution that deals with controlling the manipulation of the material at the nanoscale. It affects the characterization, improves or create new properties of the product. Nanotechnology extends to many industrial fields, including architecture. The use of nanotechnology in architecture has not only been determined by energy efficiency and sustainability but also been involved in the architectural design process. Nanotechnology may be used in architectural applications with one or more functions such as the characteristics of air purification, self-cleaning, anti-soiling, energy production, thermal regulation,

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solar radiation protection and fire protection. [3] Nanotechnology provides a new set of materials like electronic ink, biomaterials, conductive textiles that make the necessary collaboration between design and science. [4] Thus, these inventions can produce a building that is more sustainable.

Nanotechnology adopts the mechanical principles of nature by simulating the biological functions of organisms, then translated them to produce multi-functional products. It opens the new prospect for the functional materials. Multi-functions acquire new collaboration between materials engineers, designers and architects. Contemporary architects often adopt the new inventions in the architectural design. [4] Nanotechnology depends on mimicking nature to produce materials with the principle of sustainability like energy saving, recyclable and energy harvesting. [2] Every organism in nature has a cover layer to protect its body like skin, hair, feathers, shell, which provide it with comfort and its own beauty. [2] Textiles with the use of new nanomaterials, offer unique opportunities for mimicking organism's sustainable behavior.

Studying the biological systems are based on analyzing the principles of the sustainable system of organisms. [5] Many examples of the micro and nano structures are available in nature. The structure of the fabric of the plants, like coconut, palm, wood, pine cones or bamboo are arranged to get high responsive and mechanical properties. Another example is the micro hierarchical structure of glass sponge that is truss-like. Some experiments have been made to produce fabric that open or close the pores of textiles as a response to increase or decrease the moisture in the interior spaces. The silk of spiders has the properties of fineness, lustre, low weight, strength and softness. Nanotechnology makes it possible to mimic natural silk as a model to produce industrial textile with extraordinary properties. Nanotechnology aims to mimic spider to spin artificial silk in a sustainable process for many applications. The surface of the lotus leaf has the properties of self-cleaning, mimicked by coating with nano TiO_2 to be used for industrial super hydrophobic textile surfaces that remain clean. [2]

3. Nanomaterials

They can improve mechanical and chemical properties to produce multi-functional textiles. However, they present new electronic, magnetic, optical and biological functions. [3] The development of nanomaterials includes many trends, including architecture that has led to changes in the process of design itself. They enter into many architectural aspects like design processes, production and manufacture of construction materials. Some nanomaterials possess the characteristics of the ability to change their properties to provide thermal, mechanical, chemical and magnetic energy. That change is based on the material properties or depending on the user preferences. The response may be limited to the outer layer of the smart material. So, the change may be in color, shape or from one physical state to another. [6] In addition to their effect, it is possible to use nanomaterials to design architectural elements with dynamic aesthetics. It also provides flexibility and fulfilment of the requirements of architecture adaptation to external and internal conditions to meet the appropriate level of user's comfort. [3] Nanomaterials can be produced at the molecular and nano level. In future, it is expected to be used for improving the fabrication of nano-electronics, nano-machines for the industry of textiles, which can't just add new properties but lead to developing the process of producing electronic textiles. [7]

4. Smart textiles

The Latin word "textilis" is the origin of the word textile. Smart textiles can be defined as any product with fine thickness, high flexibility and multi-functional, made of any organic or inorganic materials like fibers, membrane, films, foams, metals, polymers, leather or furs. [8] Smart textiles can be described as interactive, responsive or adaptable. Their properties are offered by the embedded advanced materials and the miniaturization of components to the nano or micro scale. [9] Smart textiles were introduced to be used in the commercial industry in the nineties. The main concept was about their response to having functional properties and the ability to respond to the change of the environment.

Kuusisto mentioned a categorization for smart textile to be passive or active. While the passive only senses the environment, the active response to the stimuli that has been sensed. Another type that is called very smart, which can sense electricity, chemical reactions, pressure and light. Then, they respond, react or adapt the suitable response to the environment. Smart textiles have nano or micro devices that can be micro encapsulated, sewn, embroidered, woven, coated or printed. Chromatic are the most common materials to be used for smart textiles.

According to its type, chromatic materials can be the stimulus for electricity, electron beam, pressure or temperature. [8] Youssef argued that smart textiles can be classified into three types: The first generation (smart textiles) that responds to weather conditions. The second generation (active smart textiles) contains sensors within the same tissue that control the texture in response to direct or indirect changes. Electrically conductive polymers (conductive polymers) are used to allow the transmission without the need for electronic wiring. They are provided with two types of components, sensors or actuators. As an example, thermos-chromic materials are used to change the environment where the crystal structure changes in response to environmental changes. [6]

Alioglu classified textiles in two main types: Uncoated and coated. Uncoated textiles are made of fine fibers, then woven at the particular place. [10] examples of uncoated textiles are organic cotton fiber, fluor polymer, polyesters, polymer polyethylene, polymer polyamide (nylon fibers), polymer vectran and nonorganic fiberglass. [1] Coated textiles have been developed and available for façade applications like woven based, coated on both exterior and interior sides, like polytetrafluoroethylene PTFE, polyvinyl chloride PVC and ethylene tetra fluoro ethylene ETFE, which are the most commonly used for the contemporary architecture. ETFE textiles are made of membrane foil; they can be used for single layer, which provides low insulation and highlight transition. So, single layer is used for the exterior sun shading. Multi-layers coated textiles are used to make pillows with two or more layers that are better in thermal insulation, controlling solar lighting and flexibility. They can be printed with PV cells or any patterns. PVC membrane is made of fiberglass, coated with Teflon or silicon. [10] Multi-layers coated textiles have better thermal and less U-values. [11]

4.1. Smart coatings Smart coatings

According to their type, Smart coatings are used for their fire resistance, UV resistance, durability, fold-ability, store-ability, move-ability, self-cleaning or recycle-ability. [10] They are also used to protect textiles against the attack of high ultraviolet (UV) levels, bacteria, fungi, infrared radiation (IR), scratch, micro cracks or damage. [12] Some types of smart coating of the textiles are the following:

4.1.1. Self-healing and antimicrobial coating include spherical micro-capsules to repair the damage formation in any stage. These micro-capsules are filled with the healing agent that cure the damage. Antimicrobial coatings are used to protect textiles against microorganisms and bacterial growth, like metal-based, nanomaterials. Antimicrobial coating with metal-based are coated during textile extrusion, these metals include silver, copper, zinc, titanium. [12] Nano TiO_2 and Nano ZnO are photo-catalysts, which means that they can absorb the energy of light (photons) and decompose the bacteria and other microorganisms. [13]

4.1.2. Self-cleaning coatings are coated with self-cleaning hydrophobic nanomaterial are capable of having self-cleaning properties as anti-bacteria and pollutant degradation. So, self-cleaning coating, like nano TiO_2 and nano ZnO, simulate (Lotus Effect) of natural lotus leaf, which has micro-rough composition on its surface and it is covered by nano structured wax crystals to repel drops of water and remove dirt. [13]

4.1.3. Anti-fouling coatings like copper or heavy metal is the base of the anti-fouling coatings, which are used and available. However, there are environmental concerns about some toxic compounds. Coatings protect textiles against UV radiation of sunlight and some artificial discharge lamps by breaking down UV into harmless radiation. IR-reflective pigments or low emissivity (Low-E) coatings is used as multi - layers to protect against (IR heat) by reflecting up to 70%. These coatings decrease energy consumption and adjust comfortable temperature for the interior spaces because IR is about 53% of sunlight radiation and it is responsible for the heating phenomena. [12]

4.1.4. Self-thermos regulating coatings imitate organisms to keep their body temperature, in spite of the change of their surrounding environment. Self-thermos regulated smart textiles contains micro-capsules of phase changing materials PCM. These materials can conversely change their crystal structure from a liquid into a solid state, according to the change of the environment. [13]

4.1.5. Optical coatings are multi-layers with nano or micro thickness, made of layers of thermos-chromic transparent polymer materials (polyester and nylon. Light emitting diodes LED's lights, which interact with the environment. Optical textiles are lightweight, flexible, waterproof and don't consume energy. They can change their absorptivity, transmissivity and reflectivity depending on intrinsic and extrinsic factor; they can change their colours or become luminous and transmits signal with the aid of digital computer tools. [6]

4.2. Electronic textiles (e-textiles) and conductive textiles

They could be electrically conductive, made with plastic, steel, aluminium or carbon. Optical textiles can be used to carry computer data, signals of light or sound waves. Electrically generating textiles, as an example, polyethylene terephthalates are made to be responding to the change of the environment. PV (photo-voltaic cells) are integrated into smart textiles to generate electricity in the presence of sun's light. So, textiles work as substrates to the PV cells. [8] Electronic textiles (e- textiles) include computer and electronic micro or nano devices, like micro-controllers, electro-luminescent (EL) or active materials integrated or embedded in smart textiles, that sense or process some operation to make these textiles adaptable. They can be used by contemporary designers for interior or exterior of the architectural design like carpets, furniture, walls and façades. Smart e-textiles are responsive to the environment depending on the materials which they are made of, so they can change their shape, colour or sizes. Smart textile's properties are related to the development of conductive ink, conductive polymers, conductive threads, conductive coatings, shape memory material, piezoelectric materials, chromatic materials, thermo-chromic inks. [7] Some of these electronic devices and materials are used for electric power distribution, sensor, actuator, optical fibers, transmission of digital signals, heating resistors, flexible LED's / OLED's lights, solar cells, thermos-electric or piezo-electric devices. [13]

5. Functions of smart textiles for the architectural façade

Smart textiles are designed to be multi-functional. They are used not only for aesthetics, but also for multiple benefits, like lightness, fold-ability, ephemerality, flexibility or dynamic. [9] The applications of smart textiles are controlled by nanotechnology and digital fabrication. Environmental concerns about sustainability make architects to design façades on the principles of technical solutions and energy saving to maximize material saving. The success keys for the use of textiles in architectural façades are: 1-Reducing of weight while ensuring the highest environmental performance. 2-Minimizing the time of the cladding process and maintenance by allowing easy methods of replacing damaged parts. 3-Having a high-dimensional stability, especially if the textile is wrapped over all the building. [14] Smart textiles could be electrically conductive, made with plastic, steel, aluminum or carbon. Optical textiles can be used to carry computer data, signals of light or sound waves. Electrically generating textiles, as an example, polyethylene terephthalates are made to be responding to the change of the environment. PV (photo-voltaic cells) are integrated into smart textiles to generate electricity in the presence of sunlight.

So, textiles work as substrates to the PV cells. [8] Smart textiles provide one or more functions for the architectural façade like the following:

5.1. Enhancing strength and reducing the cost of the materials:
Smart textiles are designed to resist the high tensile strength. In addition, the ratio of strength/weight is high. So, using lightweight textiles, minimize the dead load of the façade, while they can withstand the wind loads. The use of smart textiles offers new structural properties like sharing loads, resistance to corrosion, frost, thaw and failure feedback. [11] However, the low weight and flexibility in the structure of textiles are valued for their architectural applications. [2]

Smart textiles have the capability to withstand the loads with less weight in other parts of the structures. They also minimize the amount of materials to be consumed in their production. They are also able to be recycled, which meet eco-design strategies. [8] The relation of textiles to the substructure can be categorized into three types: 1-Textiles that wrap the envelope totally, must be fixed to substructure that are made of rigid materials like concrete, steel or wood. 2-Textile that are installed as panels, will be as similar as the traditional curtain wall. 3- Textiles that are used as multi- layers' cushions are cladded to the substructure. So, the membrane doesn't cover the whole façade. Therefore, it is regarded as a screen for the sunlight protection. 4-Apneumatic structure made of air- supported multi-layers' cushions are designed to be self-standing and fixed on the foundations. [14]

5.2. Providing new aesthetic proprieties:
Smart textiles offer new tectonics; a new relationship between the structure and the elements of façade and the materials. However, this changes the traditional relation of structure and façade, the structural framework and the envelope of the architecture. [9] Smart textiles make it possible to obtain non-traditional architectural forms for the design of façades to bring motion and new aesthetics. [10] Textile has flexibility and elasticity that they allow more complex architectural forms and hybrid patterns. [6] Single or double surfaces could be adopted for free-form architectural design with the use of textiles for the replacing of glass. Otherwise, they are used for the covering glass to defuse and optimize sunlight, heating and glare. [15]

5.3. Providing the possibility of resisting weather conditions and enhancing environmental interaction and sustainability:
Smart textiles have the ability to resist one or more of weather conditions such as rain, snow, wind, UV rays, extreme weather conditions, light absorption or reflection. They control the passage of light or have acoustic insulation feature, self-cleaning and self-repairing. Innovation supports sustainability by enhancing environmental interaction, adaptability, symbiosis, intelligent systems, smart materials and durable structures. Multi-functional materials depend on the study of the flow system of energy in organisms, like trees and lungs to imitate their ability to adjust temperature in the best way. Sustainable materials as a principle may include recyclability, re-usability, durability and energy efficiency. [3] Contemporary architecture deals with multi-functional textiles by employing their full characteristics to create the creative architectural form and performance. Smart textiles are used for the sustainable goals, related to textile properties. They are better than energy conservation or production, heat isolation ability, solar heat and light transmission controlling, dynamic loads resisting, fires resisting and recycling. [10] Textiles can be easier to be re - manufactured or recycled than rigid materials. [16]

5.4. Remembering their original shape:
Smart textiles can be provided with (shape memory metal strips) that has the ability to remember their shape at the designed degree of temperature. They can be used to cover the façades to sense heat, then change their shapes according to the change of temperature. So, the change of these strips will affect the textile to be responding to the change too. [6] Shape memory materials, like metal (SMA), polymers (SMP) or ceramics (SMC), can return to their original shape after removing the stimuli like the change

of temperature, pH-value, UV-light, stress, electric or magnetic fields. So that return may be a change in position or porous size that is controlling water vapour, strain, friction or stiffness. SMA is used to control solar gain for adaptable façades. [17]

5.5. Self-cleaning:
an extra coating TiO_2 can be provided as a self-cleaning thin layer. [8] Piezo-ceramic materials change in response to changes in pressure, while phase change material changed as a response to the rise of the temperature from the crystalline to the liquid state. The third generation (Ultra Smart Textile) that has the ability of both of the self-responsive and adaptable according to the external changes. The availability of nano microprocessors that are embedded in smart textiles offer them the ability to change their shapes as a real-time response to the environmental changes. Nanotechnology offers a new concept to create what could be called as a "breathing wall" using shape memory strips of metal, which are integrated into the textile wall, [18] but the concept is still in an experimental stage.

6. Smart textiles for the architectural façade (Case studies)
The paper chooses 10 case studies that are arranged according to the date of their completion to describe the multi-functions of the smart textiles as shown in (table 1.), then compares them to detect the availability of textile's functional properties as shown in (table 2.).

Table 1. Smart textiles for the architectural façade.

The image of the case study	Case study number and the description of the smart textiles
	Case study No.1: Cheops Technology building by the Architect Sarl Arsene Henry in Canejan, France, 2019. The printed (Solits FT381) textile façade is made of a single layer, stretched and wrapped around three sides of the building and fixed to extruded profiles of special aluminum alloy. It is digitally printed with a protective layer (PU varnish). The textile provides insulation and a sun-breaker functions and it controls the temperature inside the building. [19]
	Case study No.2: Schuco Green Tower by Lena Ganswindt, Ankit Patel, Mahsa Shafghnia and Malu Lücking in Bielefeld, Germany, 2017: It is an experimental application for the electro-active Polymer (EAP) as a second skin behind the glass façade. The membrane is designed to the functions of (liquid breathing) and energy generating by movements of the textile. The generating process is based on both form finding of membrane and shape geometry and is stimulated by rainwater storage or water drops falling. [20]
	Case study No.3: Hazza Bin Zayed Stadium by the architects Pattern Design (Ltd.) in Al Ain, UAE, 2013. The desired architectural appearance based on a façade that look like (palm bole), which is made of glass-PTFE membrane panels, fixed on the diagrid steel structure. The panels have a shading function, while it allows viewing of the exterior. At night, the panels can be illuminated by LED's lights in various colors. The membrane used is anti-flame, self-cleaning, anti-dirt and 100% recyclable. [11]
	Case study No.4: Fraunhofer Institute IBMT by architect Hammeskrause in Sulzbach, Germany, 2013: The building is covered with self-structured envelope, which is made of ETFE membrane cushions. It is coated with Teflon layer (water resisting) and anti-bacterial layer, and is also resistant to dirt and UV. It is easy to repair and reflects radiation effectively [14]

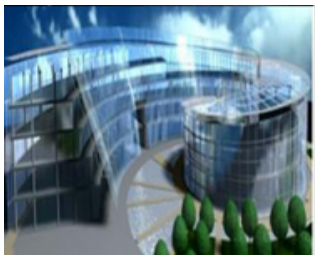
	Case study No.5: Soft House by the architect KVA Matx in Hamburg, Germany, 2013. It is an example of using the innovative textile shading which are elastic and kinetic. The flexible PTFE membrane is used in making PV curtains that obtain free energy, while they are protecting the façade from direct sunlight. The smart curtains bend smartly to face the best angle of the sun to accurate the orientation of the PV cells to have a vertical angle with the lights of the sun. The membrane also provided with LED's lighting to add enjoyment, while the surface itself carries the energy and information. [3]
	Case study No.6: Beatbox Coca-Cola by architects Asif Khan and Pernilla Ohrstedt in London, 2012: The screen of façade is made of two layers of red and white ETFE cushions supported by an aluminum frame. The membrane façade has a sculpture function with LED's lighting. It is designed with interaction devices that are integrated into the membrane to turn the building to seem as a musical instrument by making it interact through the change of lighting. [21]
	Case study No.7: Uniqlo Shinsaibashi Building by the Architect Sou Fujimoto in Osaka, Japan, 2010: The façade is covered with triple layered cushions made of (158 ETFE) membrane, which is silver printed, designed to offer weather protection and thermal insulation. It is also provided with embedded LED lights that show patterns and shapes by programming. [21]
	Case study No.8: iHome Lab by the Architects Lisher partner in Lucerne, Switzland, 2008: The façade is covered with louvers made of composite membrane that control the penetration of sunlight being curved. The louvers can also change their color at night as response to the movement of the people who approach to the façade of the building. [22]
	Case study No.9: The Allianz Arena by the Architects Herzog and de Meuron in Munich, 2005. The project has the biggest membrane covering that are made of self-cleaning and fire resistant inflated ETFE pillows, fixed on a metal net. These pillows reflect the indoor event and are provided with LED lights. The façade is illuminated with the same color of the clothes of the team that is playing. It interacts with the inside events that are happening at the time and it has PV Integration devices. [10] [23]
	Case study No.10: Gerontology Centre by the Architects Siegert in Bad Tolz, Germany, 2003: Architect's intention is creating a building as a snail shape to protect its façade and the walkways. So, the façade is covered with a single layer of ETFE membrane coated with transparent film and has the property of self-cleaning. The membrane covers the complete span of the building that makes it possible for a continuous view and the penetration of natural light. The screen can be illuminated and opened at night for effective (stack ventilation) [22]

Table 2. The smart multi–functions textiles that are used for the architectural façades of the case studies. The plus symbol + refer to the viability of function.

Textile's functional properties		NO. of Case study											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	Total	**%**
Architectural functions	New aesthetics	+	+	+	+	+	+	+	+	+	+	10	100%
	LED's lighting			+	+	+	+	+	+	+	+	8	80%
	Optical propriety			+	+	+	+	+	+	+	+	7	70%
	Strength enhancement	+		+	+	+	+	+	+	+	+	9	90%
Constructional functions	Easy installing	+	+	+	+	+	+	+	+	+	+	10	100%
	Easy repairing	+	+	+	+	+	+	+	+	+	+	10	100%
	Solar Protection	+	+	+	+	+	+	+	+	+	+	10	100%
	UV resisting	+	+	+	+		+	+	+	+	+	9	90%
	Sensing and Responding				+	+	+	+	+	+		6	60%
	Computing				+	+	+	+	+	+		6	60%
	Kinetic					+			+		+	3	30%
	Energy harvesting		+				+			+		3	30%
Environmental functions	Self- cleaning	+	+	+	+	+	+	+	+	+	+	10	100%
	Anti-bacterial		+					+	+			3	30%
	Anti-dirt	+	+	+	+	+	+	+	+	+	+	10	100%
	Recyclability			+			+				+	3	30%
	Fire Resisting	+		+	+	+	+	+	+	+	+	9	90%
	Thermal insulating	+	+	+	+	+		+	+	+	+	9	90%
	Breathing		+									1	10%

7. Conclusion

- The highest percentage (90-100%) of the smart textile's functions in the façades of the case studies, as it is shown in (table 2), is for the new aesthetics, easy installing, fire Resisting, easy repairing, water resisting, solar protection, thermal insulating, self-cleaning and anti-dirt, because they are highly demanded for the architectural, structural and environmental concerns. However, the less percentage (60-80%) of the functions, is for the LED's lighting, optical propriety, sensing/responding and computing, due to textile's benefits that are related to the attraction appearance, like playing with lights, advertising or decorating function. The much less percentage (10-30%), is for the kinetics, energy harvesting, recyclable and breathing functions, where these functions are still uncommercial. However, smart textiles are used according to the purpose that is proposed by the designer to fulfil aesthetic, structural, environmental and sustainable multi- functions, but the most used functions are about the desire for the new approach of architecture and the interesting appearances.
- Nanotechnology provides textiles with materials and devices to be smart. So, designers get a new set of materials to deal with. Multi-functional textiles, containing functional coating and energy harvesting devices, give the appropriate design solutions for lightweight, long span, low cost, sustainable, multi-functions architectural façades. This leads to the challenge and necessity for the architect to be educated with the knowledge about the properties of smart textiles in order to use them as a starting point to operate the whole design process and extend the limits of creativity of multi-functional complex patterns in architectural design.
- The future will witness a continuous development and an increasing use of smart textiles for the architectural façades because of their sustainable ecological benefits and unique appearance.

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