EFFECTS OF IRRADIATION ACCELERATED ELECTRONS ON SOME SELECTED MATERIALS FOR SPECIAL EQUIPMENT

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Abstract

The paper deals with possibilities in improving features of materials used for special equipment through irradiation by accelerated electrons. It relates with a possibility to improve mechanical features of ballistic materials used for a ballistic protection of an individual. At present time there are mainly materials of Kevlar type and ceramics. Their features, e.g. mechanical properties as well may change through irradiation of these materials with accelerated electrons. [1]. So in a practical application it would be possible to improve a ballistic protection of a bullet-proof vest as well as to decrease a weight of a vest meanwhile keeping the protection class.. The achieved results that are presented in the paper can be used also in other applications, e.g. protective clothes used in industry [2].

Keywords: irradiation of materials with accelerated electrons, ballistic protection of individual, mechanical features of materials, Kevlar, ceramics

1 Characteristics of a bullet-proof vest

Bullet-proof vest is a protective clothes designed so that it provides protection for its wearer against any kind of violent attacks. They are developed so that acts as a shield against shrapnel debris from explosion, against hits from small arms, from an attack with a knife, a shell. [1]. The vests are produced from many layers of a laminated or special woven fibre, resulting in an improved protection of a wearer. In some cases ceramics or metal is used, which with a soft layer provides a sufficient protection against larger calibres.[2] In a proposal for an advanced armour, there is a bullet-proof vest in combination with some other components, as e.g. combat helmets. Additional ballistic protective means for sides and shoulders are used in armed forces. Pyrotechnical units use heavy vests with helmets and a backbone protection. [2]

Fig. 1 *Kevlar vest with a helmet [*3].

Ballistic bullet-proof vest is divided in two main categories: heavy and light bullet-proof vests. Heavy bulletproof vests act similarly as armours worn by medieval knights. These vests are rather heavy, however they provide for a better protection than soft bullet-proof vests. Individuals can wear this type of protection mainly in a high risk of attack, but for a daily routine it is more suitable to wear more flexible kinds of protection such as light vests.

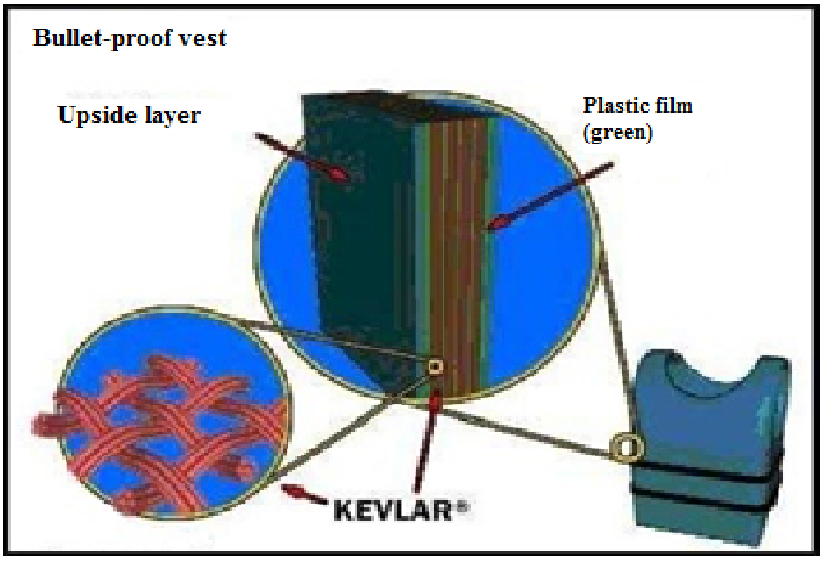


Fig. 2 *Structure of a bullet-proof vest* [3].

2 Structure and materials used in development of a bullet-proof vest

In the past various metallic and non-metallic materials were used for individual protection purposes. Special plastic materials are mostly used as special protective materials for further processing (into a form of textile fabric). They are of a high strength, resistance to dynamic impact effects, high tenacity, that predetermine them for an application as a ballistic protection. These materials have several times lower mass that steel while providing a high level of protection. There are semi-products produced from their fibres for manufacturing of protective clothes.

The synthetic protective materials being used are aramid and a special polyethylene. They are produced under various trademarks and they differ with their mechanical features. Nowadays the protective vests (bullet protection) are produced from the following kinds of special protective textiles: Kevlar, Twaron, Dyneema, Spectra, GoldFlex.

WOVEN FABRIC

Woven fabric is a sheet textile, which is formed through a reciprocal rectangular binding of warp and weft yarns. One set of yarns is arranged lengthwise and is called a warp. A warp is bond with another one, which is a perpendicular set, called a weft. The werf goes broad wise a woven fabric, from one edge to the other one. Thread count – firmness of a textile is a number of warp or weft yarns per 10mm (in softer woven fabrics) or on 100 mm (in thicker woven fabrics). Softness and density of a woven fabric depends on a thread count.

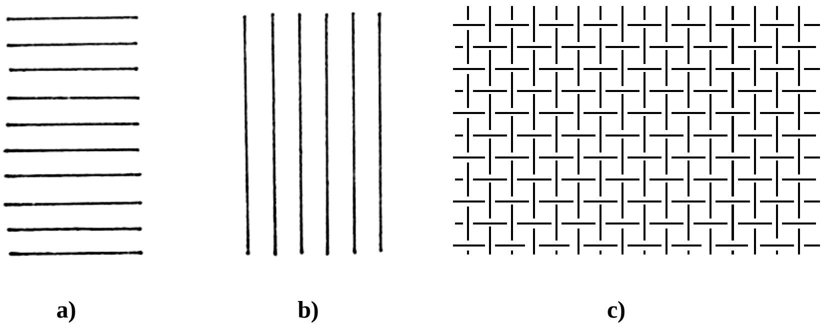


Fig. 3 *Basic set of yarns* [10]
a) weft, b) warp [5], c) binding of a weft with a warp (tabby weave) [6]

Mechanical features of special textiles are, in addition to the material features, effected with a way of binding a werf and warp set of threads when wowing (examples of binding a weft and warp are shown in Fig. 9), with an orientation of yarns of a protective layer and with folding of particular layers of a protective textile on each other. Synthetic materials being used are able to resist to projectiles with a velocity below 700 m.s^{-1} in keeping textile´s features.

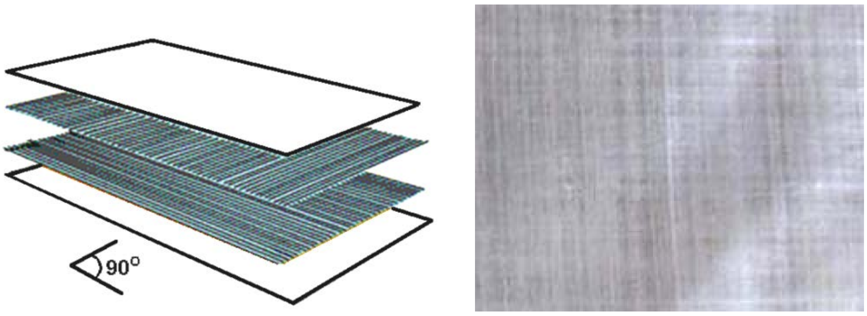
Three basic kinds of weave -tabby weave, twilled weave, basket weave, are used for woven special bullet-proof textiles (Twaron), or there are also their modifications.

NON-WOVEN TEXTILES

Non-woven textiles are textile products manufactured through more advanced manufacturing procedures. The most often their production is based on fibred layers. .Knitting and weaving are avoided in manufacturing procedures as they are expensive operations. They are replaced by mechanical and chemical processes of the strengthening of fibred layers.

Advantages of non-woven textiles reside in a possible overlaying the textile and non-textile units and in a possible regulation of a fibred ratio and its form in a resulting product.

Textiles from a special polyethylene (Spectra and Dyneema) are not woven; two layers of parallelly arranged fibres are laid on each other, whereby they are reciprocally swivelled in 90°. The both layers of fibres are inserted between foils. Protective capability of Spectra, Dyneema does not change in different impact of a projectile. Kevlar, Twaron are more sensitive to a different impact angle of a projectile. Some authors point at some small blunt shock when Spectra, Dyneema were used in comparison with textiles made of Kevlar, Twaron. [7].



a) b)

Fig. 4 *SpectraShield Protective material* [10]
a – schematic representation of layers, b - SpectraShield

ARAMID FIBRES

Aramid fibres are synthetic fibres resistant to heat that are of a high tensile strength at an excellent ratio to its weight. They are used for a production of protective ballistic textiles and as a replacement of asbestos. The aramid assignment has risen as acronym from: „aromatic polyamide“. [9]

Aramides are generally created through a reaction between an amine and carboxyl groups of elements creating AABB polymer. This liquid chemical compound is then transformed into its solid form through twisting with the sulphur acid, which can be transformed into fibres, powder or cellulose during annealing treatment. [4]

Features:

Aramid is sensitive to UV radiation, it has got a good abrasive resistance, and it is resistant to effects of organic solutions and heat degradation. It is sensitive to humidity and salt. It is non conducting and it is lightly flammable. [9]

Para-aramide fibres used for protective vests have a different structure comparing with original aramide material. Yarns are of a high ductility and a high Young´s modulus of elasticity. Specific volume weight of aramid is 1,4 $g.cm^{-3}$. [10]

Kevlar

Kevlar is a synthetic para-amid fiber with a specific volume weight about 5-times higher than the one of steel. Kevlar is a type of an aramid, consisting of long polymer chains with a parallel orientation. Strength is derived from intermolecular hydrogen bonds and aromatic stacked interactions among aromatic groups in adjacent yarns. These interactions are much stronger than Van der Vaals interactions that can be found in other synthetic polymers. Para-aramid material is Twaron, as well.

Kevlar is an organic fibre, with combination of features enabling a high strength with a low weight, a high chemical resistance and a high resistance to slitting. Kevlar is non-flammable, it does not solve, and submerging into water has no effect on a yarn.

Kevlar is pretty resistant to high temperatures, it keeps its strength and flexibility even at cryogenic temperatures (-196°C), it is little bit stronger at low temperatures. Tensile strength is reduced at high temperatures by 10-20%, and its strength henceforth decreases as early as after several hours. For example at 160°C a decrease in strength by 10% becomes evident after 500 hours. At 260°C a 50 % decrease expresses after 70 hours. At temperature of 450°C Kevlar sublimates. Kevlar is not resistant to UV radiation. Ultraviolet component of solar radiation degrade and disintegrate Kevlar therefore a protection against UV radiation must be used. In case, that Kevlar is convoluted, the fibre has a high tensile strength (about 3000 MPa), relative density of 1, 44 g/cm3 and it does not corrode.

Fig. 5 *Kevlar vest* [1].

Table 1 *Comparison of ballistic materials features [7], [9]*

Material		Maximum strength (MPa)	Flexibility module (GPa)	Density (g/cm3)	Start of a thermal degradation (Cº)
Kevlar	Kevlar 29	3600	80,0	1,44	450
	Kevlar 49	3600	130,0	1,44	450
	Kevlar 149	3400	146,0	1,47	450
Twaron	Twaron 900	2800	65,0	1,44	450
	Twaron 930	3000	125,0	1,45	450
Nomex		700	17,3	1,40	350
Dyneema	Dyneema SK60	2800	88,0	0,97	152
	Dyneema SK76	3500	125,0	0,97	152
Spectra	Spectra 1000	3000	170	0,97	147

3 Irradiation of samples with accelerated electrons

Experiment results from knowledge on a modification of mechanical features of non-metallic materials that had been exposed to irradiation through a linear electron accelerator and from official documents of the DuPont Company that had executed a similar experiment on their Kevlar material.
Irradiation with electron beam includes modification of materials through an electron accelerator. The accelerators use similar technology as the first televisions using cathode tubes. (CRT).

Modification with electron beam is used in industry mainly for:

- Spinning of polymer materials, to improve mechanical, thermal and chemical features,
- Degradation of materials due to recycling,
- Sterilization of medical and pharmaceutical products.

Spinning polymers in processing with an electron beam changes a thermoplastic material into thermo set. If the polymers are spinned, the molecular movement is prevented, so resistance to high temperature increases. This molecule lockout is an origin of all advantages of spinning, including improvement of the following features:

- Thermal resistance to higher temperatures, ageing, etc.
- Mechanical increase of tensile strength, resistance to abrasion, increased resistance to pressure, resistance to creep, etc.
- Chemical resistance to fatigue cracks, etc. [4].

Spinning is biding of adjacent molecules with bounds network induced in irradiation with an electron beam. Processing of thermoplastic materials through accelerated electrons results in improvement of these materials, e.g. increase of tensile strength and resistance to abrasion etc.

The polymers, that are usually bound through an irradiation process with beam of electron rays include polyvinylchloride (PVC), thermoplastic polyurethanes and elastomers (TPU), polybutyleneterephtalate (PBT), polyamids/nylon (PA66, PA6, PA11, PA12), polyvinylidenefluoride (PVDF), polymethylpentene (PMP), polyethylene (LLDPE, LDPE, MDPE, HDPE, UHMW PE), and ethylene copolymers, as ethylene-vinyl acetate (EVA) and ethylene-tetrafluoretylene (ETFE). Some additives are added into some polymers so that the polymer spins more easily through irradiation. [5].
Irradiation was performed on the UELR-5-1S industrial accelerator.

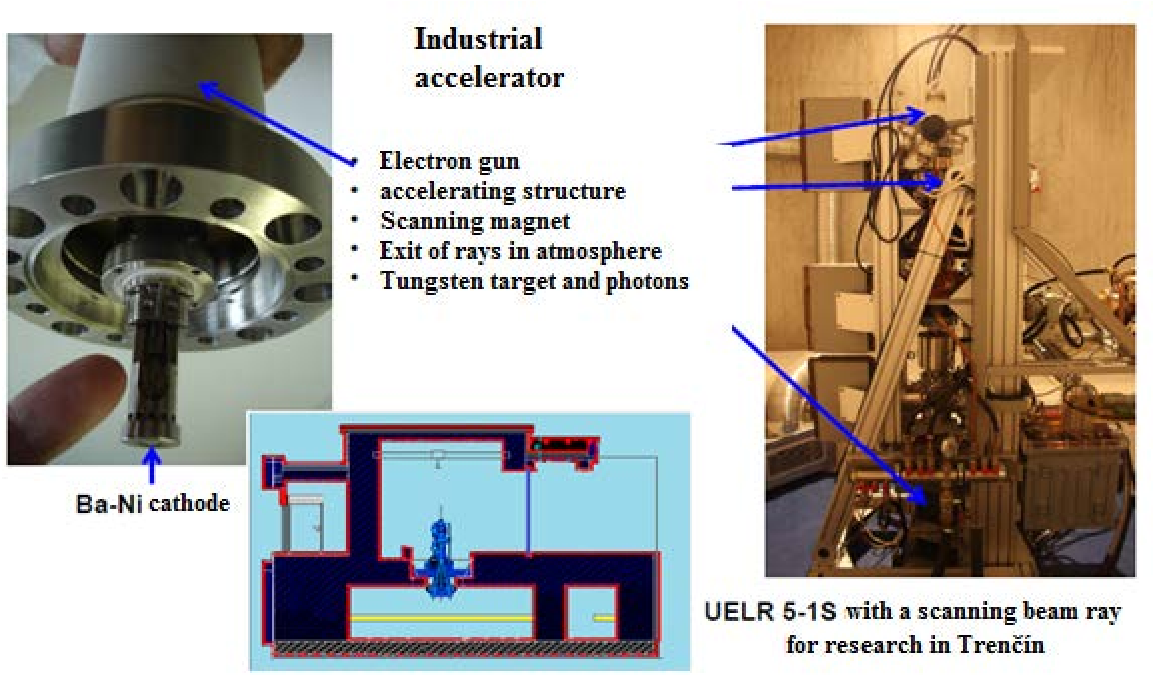


Fig. 6. *UELR-5-1S accelerator with description of main parts* [6], [8]

A precondition was defined as 4 levels of doses - 100, 300, 500 and 1000kGy.

4 Results of an experiment

Table of measured values from basic materials (no irradiation)						
Kind of material	Depth of deepening in 1st yarn rupture (mm)			Depth of deepening in a crack rise (mm)		
	Measurement N1	Measurement N2	Median	Measurement N1	Measurement N2	Median
Dyneema 585L	18,9	18,4	18,6	28,3	27,2	27,8
Twaron SBL	6,8	6,2	6,5	9,5	8,9	9,1
Twaron CT709	8,6	9	8,8	10,4	11,8	11,1
Table of measured values(irradiated materials 85 kGy)						
Kind of material	Depth of deepening in 1st yarn rupture (mm)			Depth of deepening in a crack rise (mm)		
	Measurement N1	Measurement N2	Median	Measurement N1	Measurement N2	Median
Dyneema 585L	16,9	16,2	16,5	22,8	23,2	23
Twaron SBL	6,9	6,4	6,7	9,4	10,1	9,1
Twaron CT709	9,1	8,8	8,9	11,3	12,3	11,8

Table of measured values(irradiated materials 255 kGy)						
Kind of material	Depth of deepening in 1st yarn rupture (mm)			Depth of deepening in a crack rise (mm)		
	Measurement N1	Measurement N2	Median	Measurement N1	Measurement N2	Median
Dyneema 585L	10,8	10,1	10,4	18,8	18,3	18,5
Twaron SBL	7,0	7,2	7,1	10,4	10,1	10,2
Twaron CT709	9,1	9,2	9,2	12,2	12,4	12,3
Table of measured values(irradiated materials 505 kGy)						
Kind of material	Depth of deepening in 1st yarn rupture (mm)			Depth of deepening in a crack rise (mm)		
	Measurement N1	Measurement N2	Median	Measurement N1	Measurement N2	Median
Dyneema 585L	5,1	4,9	5,0	9,7	10,3	10,0
Twaron SBL	8,4	7,9	8,2	12,1	12,7	12,4
Twaron CT709	11,1	10,5	10,8	13,6	14,3	13,9
Table of measured values(irradiated materials 1070 kGy)						
Kind of material	Depth of deepening in 1st yarn rupture (mm)			Depth of deepening in a crack rise (mm)		
	Measurement N1	Measurement N2	Median	Measurement N1	Measurement N2	Median
Dyneema 585L	1,8	1,6	1,7	4,4	4,2	4,1
Twaron SBL	9,4	9,6	9,5	12,7	13,4	15
Twaron CT709	12,1	12,6	12,5	15,4	15	15,2

TGA Thermic analysis

TGA belongs to experimental method, based in detection of a weight of a sample when heating up.
Measurements usually take place in exactly defined conditions, when with respect to a heating up process we distinguish:

- TGA isothermal, when a measurement is taken at a constant temperature. Therefore a sample is exposed to a temperature that is continuously rising or decreasing.
- TGA non isothermal, at which a sample is exposed to a temperature, which is continuously rising or decreasing in a linear way with respect to time.

The results of measurement are usually expressed in a thermo gravimetric curve, displaying a relation between weight and temperature and so it provides information on a structure of a sample, on its pyrolisis and products as well, being produced as a result of sample decay. In accordance with reviewed featured during measurements a thermo gravimetric curve can be displayed, that shows a relation between changes of weight and temperature or time designated as a normal thermo gravimetric curve. A relation between a change of velocity and temperature or time used to be designated as a differential thermo gravimetric curve. If no changes occur during measurements in a structure of a sample, the relation is expressed as a horizontal line. However, if changes occur in a structure of a sample, the weight decreases displaying on a curve as a decreasing step. Weight of a sample is measured with very accurate electronic scales. Volatile components that can release from a sample during measurement are defined with a mass spectrometer with a TGA module [1, 2, 3, and 4].

Through effects of various temperatures the weight of a sample can decrease or increase in special chemical – and-physical actions. Through an effect of a high temperature the weight of a reviewed sample usually decreases based on evaporation of volatile components from a sample. However in some cases the weight of a reviewed sample may also increase based of humidity adsorbed from atmosphere. [1, 3, 5, 9].

TGA measurement takes place with special highly precise thermo scales, when a sample is places on a scale made of platinum, corundum or other suitable material. A scale with a sample is usually placed on a heater that is computer-controlled. When this method is applied, atmosphere is controlled as well, usually through gaseous nitrogen. The gases released from an oven can be then directed to a gas chromatograph or IR spectrometer. Majority of Instruments for TGA enable using isothermal and dynamic heating or cooling cycles or maintaining certain temperature, depending on isothermal TGA or non-isothermal ones. So TGA is very useful in reviewing various kinetic processes and liquids related with a changed of a weight of a sample being reviewed [2, 3, 4, 10].

Ballistic test

An experiment was performed in SKTC-112 testing facility in Lieskovec by ČSN 39 5360 standard. Ballistic board made of AKYMATROS material was used for such testing.

Firstly a test with a testing body in a cylinder shape was performed on a testing sample with a temperature of 22 °C. The body was dropped from the height of 2 m. The test was performed after shooting as well. The measured values are in the Table 2.

Table 2 *Results of a ballistic test*

	Measurement N. 1 [mm]	Measurement N. 2 [mm]	Measurement N. 3 [mm]	
T before	27	28	27	
T after	27	27	26	

9 mm LUGER was used for a ballistic test with a projectile weight of 8g and its velocity 410 ±10 $m.s^{-1}$. The measured values were a dull trauma in a background material and its diameter. Particular measurements are recorded in Table 3.

Table 3 *Results of measurements from a ballistic test*

	Parameters	Measurement N. 1	Measurement N. 2	Measurement N. 3	Median
100 [kGy]	Velocity [m/s]	416,6	411,9	416,8	415,10
	Dull trauma [mm]	30	29	28	29,00
	Trauma diameter [mm]	70	65	65	66,67
200 [kGy]	Velocity [m/s]	413,7	418,1	416,1	415,97
	Dull trauma [mm]	28	28	27	27,67
	Trauma diameter [mm]	70	65	70	68,33
300 [kGy]	Velocity [m/s]	413,7	414,6	414,7	414,33
	Dull trauma [mm]	27	27	28	27,33
	Trauma diameter [mm]	55	50	60	55,00

5 Conclusion

The paper and a performed experiment were aiming to verify possibilities how to achieve features of materials being used in production of special equipment, namely bullet-proof vests. It will enable an increase of a protection of a ballistic vest and a decrease of the vest weight, whereby the resistance class will remain the same. Achieved knowledge has proved a presumption, that irradiation can improve mechanical features of some chosen materials. A working place of authors is ready to go on in research in form of experiments in improving not only mechanical features of materials after having irradiated them with accelerated electrons. Application of such adjusted materials for practice is wide, e-g. reconnaissance equipment, automation equipment etc.

References

[1] M. Keliar: Advanced ceramics for ballistic protection, Doksem 2013 – Technológ 2013, Žilina: Žilinská univerzita, ISSN 1337-8996, Vol 03, 2013, p. 117 – 120.
[2] M. Keliar: Inovations in the area of ballistic protection, Transfer inovácií Vol 25, 2013, ISSN 1337-7094 s. 150 – 152.
[3] M.Keliar., J.Mikurčík: Tatraruv 250, ELENEM 2013: 1. Medzinárodná vedecká konferencia Aplikácia elektroniky, energetiky, einformatiky a mechatroniky v špeciálnej technike a krízovom manažmente. Trenčín: TnUAD, 2013, ISBN 978-80-8075-601-7.
[4] Z. Jonšta: *„Technické materiály II“, 126*, ISBN 978-80-248-2574-8, 2012.
[5] J. Jussila: *„Wound ballistic simulation: Assessment of the legitimacy of law enforcement firearms ammunition by means of wound ballistic simulation.”* Helsinki: Academic Disertation, 2005, p. 112, ISBN 952-10-2209.
[6] P. Klučina, A. Romaňák: *“Člověk, zbraň a zbroj v obraze doby 2 : 17.-20. Století”*, 1. vyd. Praha : Naše vojsko, 1984,
[7] <https://www.iamtheironman.com/body-armor-materials.htm>
[online], [8.1.2014]
[8] <http://inventors.about.com/library/inventors/blforensic3.htm>
[online], [29.12.2013]
[9] <http://www.safeguardarmor.com/articles/body-armor-materials/>
[online], [4.2.2014]
[10] E.Šprync, J. Foltýn, J. *„Textilné materiály“*, Bratislava: Alfa, 1991, p. 351, ISBN 80-05-00796-5.