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PREDICTING THE BALLISTIC STRENGTH OF ULTRA HIGH MOLECULAR WEIGHT POLYETHYLENE/FIBER COMPOSITES BY IMPLEMENTING FULL FACTORIALEXPERIMENTAL DESIGN

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Abstract

The purpose of the study is to predict the ballistic strength of hard ultra-high molecular weight polyethylene fiber/phenolicballistic composites by implementing the full factorial experimental design. When designing ballistic composites two major factors are the most important: the ballistic strength and the weight of the protection. The ultimate target is to achieve the required ballistic strength with the lowest possible weight of the protection. The hard ballistic UHMWPE/phenolic composites were made by the open mold high pressure, high-temperature compression of prepreg made of plain woven UHMWPE fiber fabric and polyvinyl butyral modified phenolic resin.The preparation of the composites was done in accordance to the 2^2 full factorialexperimental design. The areal weight of composites was taken to be the first factor and the second – fiber/resin ratio. The first factor low and high levels are chosen to be 2 kg/m^2 and 9 kg/m^2, respectfully and for the second factor – 80/20 and 50/50, respectfully. The first-order linear model to approximate the response i.e. the ballistic strength of the composites within the study domain (2 – 9) kg/m^2 x (80/20 – 50/50) ratio was used. The influence of each individual factor on the response function is established, as well as the interaction of the two factors. It was found out that the estimated first-degree regression equation with interaction gives a very good approximation of the experimental results of the ballistic strength of composites within the study domain.

Keywords: *UHMWPE fiber, ballistic composites, factorial design, regression equation, V50.*

INTRODUCTION

Since the beginning of armed conflict, armor has played a significant role in the protection of warriors. In present-day conflicts, armor has inarguably saved countless lives. Over the course of history—and especially in modern times—the introduction of new materials and improvements in the materials already used to construct armor have led to better protection and a reduction in the weight of the armor. Body armor, for example, has progressed from the leather skins ofantiquity, through the flak jackets of World War II to today's highly sophisticated designs that exploit ceramic plates and polymeric fibers to protect a person against direct strikesfrom armor-piercing projectiles and fragments of explosive devices. The advances in vehicle armor capabilities have similarly been driven by new materials.Modern optimal protection needs to be achieved without compromising practical constraints such as weight and cost reductions. One of the "new "materials which is widely used in the last three decades is ultra high molecular weight polyethylene (UHMWPE) fiber.

UHMWPE fiberis a crystalline molecule that consists of long molecular chains that are highly oriented and show strong intermolecular chain bonding. It is made from bulk UHMWPE by gel spinning process. In normal polyethylene the molecules are not oriented and are easily torn apart. In a gel spinning process the molecules are dissolved in a solvent and spun through a spinneret. In the solution the molecules that form clusters in the solid state become disentangled and remain in that state after the solution is cooled to give filaments. As the fiber is drawn, a very high level of macromolecular orientation is attained resulting in a fiber with a very high tenacity and modulus [1,2,3]

The resounding characteristic of UHMWPE fiber is its remarkable strength. This very strong fiber has made its biggest impact in the ballistics defense where it's used in bulletproof vests and helmets. It is stronger than fiberglass and almost ten times stronger than steel on a kilogram-for-kilogram comparison. It is the one of the strongest man-made fibers.Itshigh elongation at break, high modulus and high strength make it the idealreinforcement solution for reducing weight and for combating increasing threats [4]. Very high strength of UHMWPEfibers is essential factor in the energy absorbing mechanism needed to defeat dynamic ballistic impact or to mitigate blast. This makes the fibers the material of choice for:

- Ballistic vests and helmets
- Blast panels that protect against landmines
- Engineered ballistics panels (either stand-alone or as part of a combined solution)
- Spall liners

By combining fibres with an appropriate resin matrix system – typically phenolic – essential mechanical and physical properties can be engineered into the composite.

Because of their high strength/weight ratio UHMWPE fibers are mainly used forballistic vestsor as reinforcements for composites (helmets, panels)for personal protection[5,6].

Most military casualties which are due to high speed ballistic projectiles are not caused by bullets. The main threat is from fragmenting devices. In combat, this means, in particular, grenades, mortars, artillery shells, mines, and improvised explosive devices (IEDs) used by terrorists.

One strategy of experimentation that is used extensively in practice is the one-factor-at-a-time (OFAT) approach. The OFAT method consists of selecting a starting or baseline set of levels, for each factor, and then successively varying each factor over its range with the other factors held constantat the baseline level. After all tests are performed, a series of graphs are usually constructed showing how response variable is affected by varying each factor with all other factors held constant. The major disadvantage of the OFAT strategy is that it fails to consider any possible interaction between the factors. The correct approach to dealing with several factors is to conduct factorial experiment. This is an experimental strategy in which factors are varied together, instead one at a time, and enables the experimenter to investigate the individual effects of each factor and to determine whether the factors interact.

2. EXPERIMENTAL PROCEDURE

Experimental composite plates were made by impregnation of UHMWPE fiber fabric with thermosetting phenolic resin modified with polyvinylbutyral. Intrinsically brittle phenolic resin is modified for flexibility which better contributes to kinetic energy absorption of the high-speed impact and its dispersion in the adjacent layers. As reinforcement plain woven UHMWPE fiber fabric with areal weight of 295±8 g/m^{2}was used. The fabric was surface modified for better adhesion with phenolic resins. The composites i.e. laminates were produced by open-mold compression at high pressure and temperature of 155 ^{o}C within 150 minutes for fully curing i.e. cross-linking of the resin. No post-curing treatment was done.

During the impregnation several factors wereobserved(speed of impregnation, resin viscosity, metering rolls gap in the impregnating machine) so that the required resin pick-up and its content in the prepreg was achieved.

The areal weight of the composites was adjusted simply by adding more prepreg layers in the press packet from the lowest to the highest area weight in accordance to the experimental design.

In the 2^2 full factorial experimental design (FFED) the areal weight of the composite is taken to be the first factor, and the second factor - fiber/resin ratio. For the first factor the low and the high levels are 2 kg/m^2 and 9 kg/m^2, respectfully, and for the second factor – resin content of 20% and 50 % (which corresponds to fiber/resin ratios of 20/80 and 50/50, respectfully).

Within this relatively narrow areal weight region, which is of importance only for panels for personal ballistic protection, the liner dependence of ballistic strength vs. areal weight was assumed. That's why the first-degree model with interactions was used to predict the response i.e. the ballistic strength of the composites within the study domain (2 – 9) kg/m^2 x (20%– 50%) resin content.

The full factorial experimental designallows to make mathematical modeling of the investigated process in a study domain in the vicinity of a chosen experimental point [7, 8]. To cover the whole study domain, for the areal weight of the composites the experimental point 5,5± 3,5 kg/m^2,was chosen, and for the resin content , the experimental point 35 ± 15 % (which corresponds to previously defined levels for fiber/resin ratios)

All test are done with a standard 1,1g chisel-nosed fragment simulating projectiles which are non-deformable, made of quenched and tempered steel with a flat rectangular tip. The ballistic limit velocities, V50, arecalculated in accordance to the STANAG 2920 calculation method. V50 value presents 50 % probability of penetration and is statistical test developed by the US military. In accordance to the FFED procedure 4 (2^2) trails are needed, i.e. all possible combinations of the variables are tested.

The coding of the variables is done in accordance to table 1.

Table 1. Coding convention of the variables

	Areal weight, kg/m^2	**Resin content, %**
Zero level, $x_i=0$	5.5	35
Interval of variation	3.5	15
High level, $x_i=+1$	9	50
Low level, $x_i=-1$	2	20
Code	x_1	x_2

4. RESULTS AND DISCUSSION

The results of the test are presented in Table 2 together with the experimental matrix.

Table 2. Experimental matrix with results

Trials	Areal weight, x_1	Resin content, x_2	Interaction x_1x_2	UHMWPE composite V50, (m/s)
1	-1	-1	+1	268.9
2	+1	-1	-1	580.6
3	-1	+1	-1	248.0
4	+1	+1	+1	545.8
-1 Level	2 kg/m^2	20%	-	-
+1 Level	9 kg/m^2	50%	-	-

By implementing the 2^2 full factorial experimental designit was found out that response function with coded variables, y_k,was:

$$y_k = 410{,}825 + 152{,}375x_1 - 13{,}925x_2 - 3{,}475x_1x_2$$

and in engineering variables, y_n:

$$y_n = 191{,}1286 + 45{,}8524x_1 - 0{,}5643x_2 - 0.0662x_1x_2$$

In the FFED the term $x_1x_2$is the interaction between factors which also has influenceon the response, in our case V50 value.

Analyzing the regression equation it can be find out that the main positive contribution to the V50 is given by the areal weight of the composites i.e. V50 is directly proportional to the areal weight. On the other hand, the resin content of the composite has inversely proportional effect on ballistic strength which means the higher the resin content the lower the ballistic strength. The interaction of the two factors, with coefficient of -0,0662 has slightly negative effect on the ballistic strength which is of secondary order compared to areal weight and resin content of the composites.

To validate the equation theoretically calculated results arecompared with experimental values for composites with areal weight of 2, 3, 4, 5, 6, 7, 8, 9 kg/m^2 and constant resin content of 35%.This comparison can be done with any other value for the resin content as long as it is within the study domain. The results are presented in Figure 1.

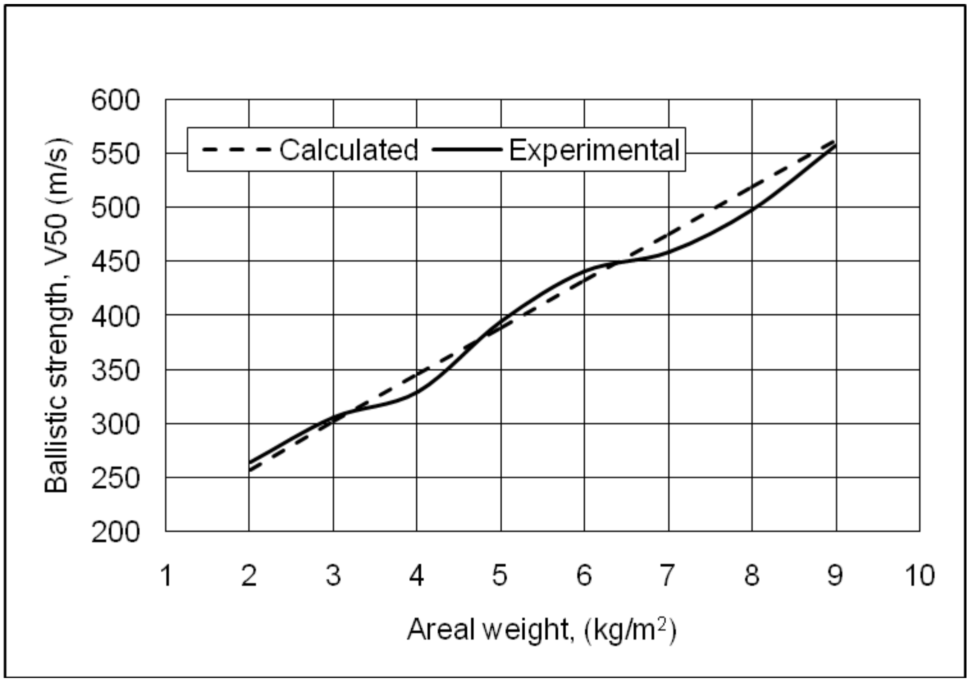

Figure 1. Ballistic strength vs. areal weight of composites

As it can be seen from Figure 1 there is a very good match between calculated and the experimental values. All calculated values are placed in a straight line which is in accordance with the assumed model of the experiment and are in close proximity of the experimental data.

CONCLUSION

- For a range of the areal weight and for a range of the resin content the experimental measurements of the ballistic strength of composite laminates were carried out by implementing the 2^2 full factorial experimental design. A correlation equation was established for V50 as a function of the areal weight and the resin content of the composites.
- A very good agreement was found between experimental and calculated values. It was observed that if the study domain is precisely established the full factorial experimental design can be employed in order to give good approximation of the response i.e. V50 value.
- V50 is directly proportional to the areal weight of the composites and inversely proportional to the resin content, the areal weight being more dominant factor than the resin content

REFERENCES

[1] D. E. Demco, C. Melian, J. Simmelink, V. M. Litvinov and M. Möller, "Structure and Dynamics of Drawn Gel-Spun Ultrahigh-Molecular-Weight Polyethylene Fibers by 1H, 13C and 129XE NMR," Macromolecular Chemistry and Physics, 211(2010) pp. 2611-2623.

[2] P. Smith and P. J. Lemstra, "Ultrahigh Strength Polyethylene Filaments by Solution Spinning/Drawing", *Journal of Materials Science*, Vol. 15, No. 2, 1980, pp. 505-514.

[3] M. J. M. Jacobs, "Creep of Gel-Spun Polyethylene Fibres," Ph.D. Thesis, Eindhoven University of Technology, Eindhoven, December 1999.

[4] R. Marissen, L. Smit and C. Snijder, "Dyneema Fibers inComposites, the Addition of Special Mechanical Functionalities,"*Conference Proceedings*, *Advancing with Composites* 2005, Naples, October 2005.

[5] J. G. H. Bouwmeester, R. Marissen and O. K. Bergsma,"Carbon/Dyneema® Intralaminar Hybrids: New Strategyto Increase Impact Resistance or Decrease Mass of Carbon Fiber Composites," *ICAS*2008 *Conference Anchorage*,Alaska, September 2008.

[6] I. M. Ward and P. J. Hine, "The Science and Technologyof Hot Compaction," *Polymer*, Vol. 45, No. 5, 2004, pp.1413-1427.

[7] G.Box, D.Behnken, "Some new two level designs for the study of quantitative variables.", Technometrics 2, pp.455-475.

[8] W. Hunter, S. Hunter, "Statistics for Experimenters: Design, innovation and discovery", John Wiley and Sons, 2005.

[9] M. P. Vlasblom and J. L. J. van Dingenen, "The Manufacture,Properties and Applications of High Strength, High Modulus Polyethylene Fibers," In: A. R. Bunsell,Ed., *Handbook of Tensile Properties of Textile and TechnicalFibres*, Woodhead Publishing Ltd., Cambridge, 2009. doi:10.1533/9781845696801.2.437

[10] P. M. Cunniff, "Dimensionless Parameters for Optimizationof Textile-Based Body Armor Systems", *Proceedingsof* 18*th International Symposium on Ballistics*, *SanAntonio*, November 1999.

[11] M. J. N. Jacobs and J. L. J. van Dingenen, "Ballistic ProtectionMechanisms in Personal Armour," *Journal ofMaterials Science*, Vol. 36, No. 13, 2001, pp. 3137-3142.

[12] M. J. N. Jacobs and J. L. J. van Dingenen, "Ballistic ProtectionMechanisms in Personal Armour," *Journal ofMaterials Science*, Vol. 36, No. 13, 2001, pp. 3137-3142.

[13] H. van der Werff, U. Heisserer and S. L. Phoenix, "Modellingof Ballistic Impact on Fiber Composites," PersonalArmour Systems Symposium 2010, Quebec City, September 2010.

[14] H. van der Werff and A. J. Pennings, “Tensile Deformationof High Strength and High Modulus Fibers,” *Colloid& Polymer Science*, Vol.269, No. 8. pp.747-763