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Aramid, steel, and glass: characterization via cut performance testing, of composite knitted fabrics and their constituent yarns, with a review of the art

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Abstract Aramid, glass, and steel have been compared for their performance in composite forms in protective applications, which are not the most usual ones. After underlining the importance of cut protection, a rather extensive review of the art in the domain of cut performance reveals that a good basis has been established, still leaving space for the study of non-coated, less uniformly interlocked composite yarn assemblies in the form of knitted structures or woven ones. Slightly departing from the traditionally friction-driven cut mechanism, those structures are distinguishable. This offers some elements for the long-awaited clarification of normalized test differences. Statistically, relevant families of commercial or semi-commercial products have been selected to address simultaneously the variability and the performance boundaries of those materials using instrumented ASTM cut equipment to obtain a "smarter" response of the material performance during its testing and to perform a "more sophisticated" data analysis beyond usually specified ones. The attempts to analyze more localized physical events open the door to micro or nanoanalysis of the fracture mechanism during the cut event which may differ from the traditional friction analysis. The contribution of meltable companion fillers, although not being the core of the study, could be translated to applications where those fillers become functional elements further improving the performance and synergism of the three basic elements, aramid, glass and steel. Previous study on the tribological properties of Kevlar® (DuPont's registered trademark) composite fabrics stands as a natural prolongation of this study when applied to the knitted composite structures of this study.

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Introduction and review of the previous contributions

The mechanical properties of aramid materials underlie their significant commercial utilization in many areas: in order to name a few, as illustrated on Fig. 1, communications, including transportation as well as transmission, leisure and sports, life protection, and health and safety in general, have been tremendously improved and adapted to modern technologies in part thanks to the aramids.

Steel has been used for a very long time as a reinforcing material; mostly known as "the" concrete reinforcement of choice; steel has been used in other applications such as a textile companion, for example, in knitted, woven, or braided forms.

Glass has evolved tremendously over time from, a "reputation" of being a rather brittle material, to a medium-to-high performance reinforcement. In order to give just a few applications of this type: glass is used as a key composite ingredient in the car industry or as a traction force element in optical cables.

The three types of material cited here above are now being fairly widely used in the individual protection such as hand protection. They are generally considered as High Cut Performance Materials, referred hereafter as HCP.

The number of portable machines, their performance, and the "do-it-yourself" tendency have largely contributed to the increase of hand injuries [1–4] in the domestic field and to a lesser extent in the professional area. In the professional activities, the awareness and the prevention regarding hand injuries have substantially contributed to containing the injury level; nonetheless, the hand protection remains an area where the room for improvement is substantial.

As per a relevant 2001 literature review [2], acute hand injuries are the leading occupational injury in the emergency departments in the United States, affecting up to

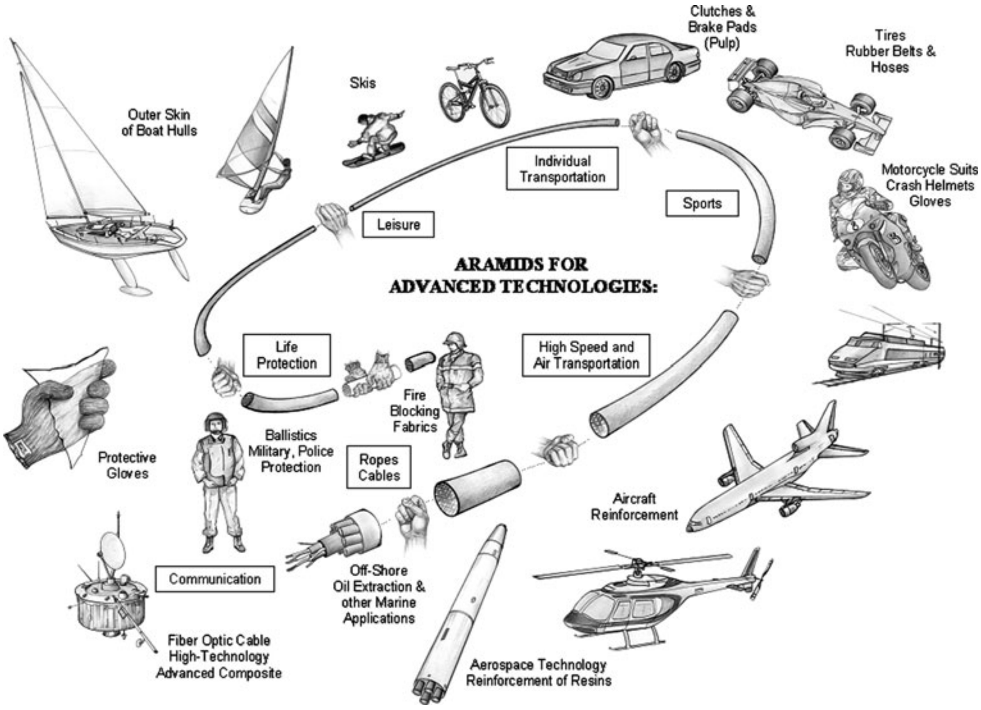


Fig. 1 Applications of para-aramid fibers

30% of injured workers. Finger cut and laceration of fingers are classified third in the number of lost work cases.

The hand is by far the most frequently injured part of the body at work being at the mercy of large varieties of machines, stationary or portable, in production as well as construction areas. In a study [3] carried out in rapidly transforming areas, such as Hong Kong, which evolved from a manufacturing to a service-based economy, the authors found that nearly 50% of the emergency occupational injury treatment at one of the city hospitals involved the hand.

The direct and indirect costs of hand injuries is taken into account in a 2006 study conducted in the UK [1], which also confirms that those injuries represents a fifth of all emergencies of most hospitals inducing a cost of over $150 millions.

The indirect expenses and the emotional consequences for the patients are rarely separated from the whole expenses. Gustafsson and Ahlström [4] have conducted a survey to quantify and provoke the momentum to address such types of distress, which have societal and economic consequences.

Thanks to the hand protective apparels, made generally of high performance fibers and materials cited previously, the situation is improving on a worldwide basis. General guidelines about hand protection are provided in the ANSI/ISEA 105-2000 [1].

Thanks to Tejani et al. [5], a cut testing basis has been established, involving the cooperation of seven laboratories in an interlaboratory test program, followed by the adoption of improved norm specifications taking into account the already well-adopted European norm.

Lara et al. [6] as well as Massé et al. [7] have been part of the pioneering team for the development of the ISO cut norm. They have reinforced and complemented the approach of Tejani et al. [5] in the ASTM arena.

Later, Yarborough and Schiffelbein [8] also underlined the improvements in the measurement of the cut protection performance by way of a series of revisions of the ASTM F 1790 initially developed on the basis of the study done by Tejani et al. [5]; the said revisions are still under implementation and awaiting further validation although already adopted.

Previously, rubbers and cross-linked polymers were of particular interest in the scientific approach of the cut mechanism [9, 10]. Lake and Yeoh [9] have paved the way of the interpretation of the cut of rubbers under minimized friction. A constant-angled, Y-shaped sample of rubber is being cut by the teflonized edge of a razor blade at very much reduced speeds compared to the speed currently used for the cut testing of protective clothing. Both a saw tooth-wave stick and slip phenomena and a catastrophic cutting were observed during cutting. Those are intrinsically associated with the mode of testing and the nature of the continuous and homogeneous rubber layer. Although these observations are at the antipode of the “fracture” mechanism associated with the tearing of fibrous interlocked knitting layers with stress concentration nodes, one may pay attention to the importance of the deformation of the matter as described by Lake and Yeoh [9]. The intrinsic strength of the material and the frictional contribution have been usefully separated. They remain fundamentally different from the one which could be observed when testing knitting structures where material concentration at the interlocking nodes contributed to a highly heterogeneous layer in terms of intrinsic strength. Rebouillat and Steffenino [11, 12] have proposed series of cycles consisting of Densification–Compression–Cut–Relaxation (DCCR) to describe the cut mechanism associated with the cut of fibrous materials in knitted or, to a lesser extent, woven forms. Depending on the elastic response of the vulcanized rubber and the tearing energy, the cut mechanism varies considerably; one may expect a more consistent cut mechanism when knitted structures are tested, whereas if these are coated, then the initiation of the cut process will be driven by the coating and its elastomeric nature.

The revealed induced tear mechanism is largely dependent on the sharpness on the crack tip induced by the cutting and, therefore, unlikely to play a similar role in the cut of intermingled structures such as knitted ones where crack development is constantly interrupted.

Gent and Wang [10] recognized that the energy required for cutting crosslinked polymers amounts to the sum of the energy associated with the rupture of the molecular chains of the polymer and the energy dissipated in the viscoelastic and plastic processes. Also using the Y-shaped samples, Gent and Wang [10] brought the right level of questioning regarding the various percentages of contribution of those two types of energy factor. They also provided revealing examples in favor of a dominant plastic yielding factor. Gent and Wang [10] clearly showed that there is no simple way to avoid this dominant element. Associating tear energy with cutting-induced fracture energy appears to be difficult in such cases involving homogeneous polymeric layers.

While showing that the cutting energy depends on the molecular weight of the crosslinked entities, Cho and Lee [13] confirmed that other energy dissipation processes have to be including filling the gap between the experimental data and the bond rupture calculations. Using a Williams–Landel–Ferry (WLM) equation to “normalize” the data, Cho and Lee also clearly demonstrated the viscoelastic dominant contribution, outlining, at the same time, the higher value of the tear energy compared to the cutting requirement.

Given the nature of the materials of this study, i.e., glass, steel, and aramids, and their limited viscoelastic properties, it is unlikely that previously discussed studies can be sufficient predictors of the behavior of such materials in interlocked layers with stress concentration nodes.

An intermediate step to surmount this fundamental challenge is brought by Thi et al. [14, 15] involved in the testing of protective apparels generally made of textile coated with polymers and rubbers. Their cut mechanism fundamental analysis benefits from previously privileged modes of fracture including the intrinsic material strength and the frictions occurring laterally as well as at the tip of the cutting edge. In order to further investigate the cutting phenomena, the ISO [16] testing equipment was instrumented, similar to the ASTM test equipment instrumented by Rebouillat and Steffenino [11].

Penetrating forces versus sliding forces are monitored. Thi et al. [14, 15] confirm the greater importance of the gripping lateral forces versus the normal forces. In their approach, Thi et al. [14] have privileged the analysis of the cutting mechanism in the presence of friction. In doing so, they were able to contribute more clearly to a scientific view of the contribution of the viscoelastic properties and the structure of the materials as well as the operating conditions of the studied cutting event, such as speed. Thi et al. [17], more recently, underlined the progress in the characterization of the cutting resistance of protective materials with a focus on rubberized materials where friction impeachment to the penetration of a blade is a dominant characteristic.

Along these lines of thinking, Rebouillat and Steffenino [11] brought some insight of the speed, temperature effects, wet conditions, and the coating contributions and also of other aspects of the speed profile, which differs significantly from the one norm attributed to the other refs. [11, 12, 18], namely, the artefacts generated by various spot coatings… Thi et al. [14] went further in proposing a theoretical model, which integrates those properties and conditions. This model appears to be in agreement with the experimental data for the type of material selected, mostly coated textiles and films.

Rather than further exploring the above path, we have selected to bring clarification of the difference between two cut mechanisms involved in the EN and the ASTM or ISO cut measurements. The EN norm is still very broadly used in the Pacific region as well as in Europe, while the ASTM is more dominantly used in the Americas. The ISO is in the process of becoming more universally used across continents.

There is, therefore, an acute need to link those approaches to cut measurements and to bring some level of scientific clarity for material specifications using one norm or the other. Without any intention to correlate in service performance versus the norm data, we have focused on the practical conditions and materials used in the trade. All the samples are from the trade or are industrial prototypes.

On a purely scientific standpoint, textiles, which are interlocked structures, can be challenging given the variation of the material density exposed to the blade edge. The tendency to have entanglement between the fibers and the blade, especially with non coated textiles renders the challenge even bigger.

The selection of HCP materials such as steel, aramids, and glass brings additional value to the practical and fundamental understanding since the cut performance differences, especially between EN and ISO–ASTM, are amplified. The viscoelastic limitations of those materials invite a further scientific interest.

Aiming at improving the interpretation of the measured cut level, Rebouillat and Steffenino [11, 12], Rebouillat and Aramids [18] pointed out a few difficulties associated with the testing and the data interpretation of articles reinforced with conductive material such as steel or reinforced with brittle material such as glass. Supported by other research data, Lara et al. [19], as further described in this study based on previous study [11], reported some significant differences related to the testing via one norm procedure or the other. For example, as initially anticipated by Lara et al. [19], ASTM and EN methods do not converge when glass reinforced articles are being tested.

Applying more science in the practical field is a key objective although applying more interpretational criteria in favor of one fracture mechanism versus the other remains of paramount importance. More precisely:

The prime objective of this study is to underline limitations and differences associated with the cut testing of materials, which contain a plurality of the three important classes of components, mentioned above.

The second objective is to further contribute to a reflection on norm harmonization, which has been taking place for more than a decade [11, 12, 18].

The third objective of this article is to underline the synergism and limitations of combined materials in terms of cut performance as measured using testing methods described in the existing norms.

From a material science standpoint, *the fourth objective* of this study is to contribute to a better understanding of the three basic reinforcing elements, especially in more advanced and demanding applications using in part the “smart instrumentation” of equipment used in relevant norms. The micro and nano fracture mechanisms as outlined by SEM analysis are also useful elements in terms of the material science approach.

It is not an objective of this study, to correlate the results and tendency provided here with the real risk encountered in the field. Therefore, this study cannot constitute a direct basis for risk analysis but can constitute a guiding framework for an improved understanding of the factors, which may influence the cut performance of protective equipment.

The study proposed in this article appears, therefore, naturally fitting in the continuous improvement of data generation and analysis initiated by the contributors mentioned above. The material science impact is significant given the importance of the three selected materials, glass, steel, and aramids, in civil engineering, military applications, transportation, and life protection, in general, to cite just a few domains.

Cut testing methods and materials

Cut testing methods

Today, there are three standards used to evaluate cut resistance of knitted or woven textiles: ASTM F1790, ISO 13997, and BS EN 388. In ASTM F1790 standard [20] and ISO 13997 [16], the cut resistance of a material is expressed as the cutting force applied to a straight blade required to cut through the sample in a stroke of 20 mm. In the BS EN 388 test method, cut resistance level is based on the ratio of the number of cycles of a circular blade required to cut through the sample to the mean cycles required to cut through a reference cotton fabric. This ratio is called the cut index.

The first standardized cut test method was developed in France in 1987 (BS EN388 [21], hereafter called EN method) followed by a method developed by the American Society for Testing Material, an American standard testing method (ASTM-F1790-97/04 [20], hereafter called ASTM method) in 1997, and its most recent international adaptation via the International Standardization Organization (ISO-13997 [16], hereafter called ISO method). General guidance about hand protection is summarized in the ANSI/ISEA 105-2000 [1], which relates to those various norms.

Each testing procedure is described in the norm documents, [16, 20, 21], mentioned above. The three related test equipments are depicted in Fig. 2 with a schematic representation of the blade orientation, the load force application point, and the blade displacement. The sample in each of the three cases is located underneath the blade on the sample holder as shown on Fig. 2 bottom part.

There are similarities between the ASTM and ISO procedures and equipments, but there are fundamental differences between these two and the EN equipment and test method.

The EN test method is based on the measurement of the substrate cut resistance when submitted to the cutting effect generated by the rotation of the circular blade on the sample tested, which is under a relatively moderate pressure provided by a 5-N load force applied on the blade as detailed in [11, 12].

The ASTM and ISO methods, on the other hand, are based on the measurement of the load necessary to provoke the cut-through of the sample after a sliding distance of the rectangular blade of 20 mm (the most recently adopted

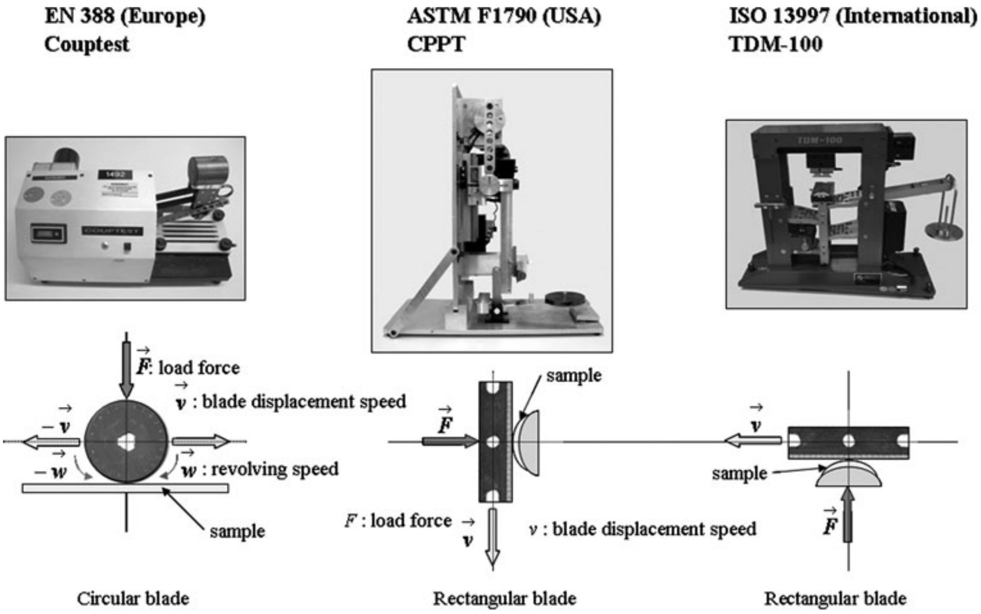


Fig. 2 Test equipments (*top*) with schematic representation (*bottom*) of the force application, blade displacement, and blade orientation, (EN, ASTM/ISO)

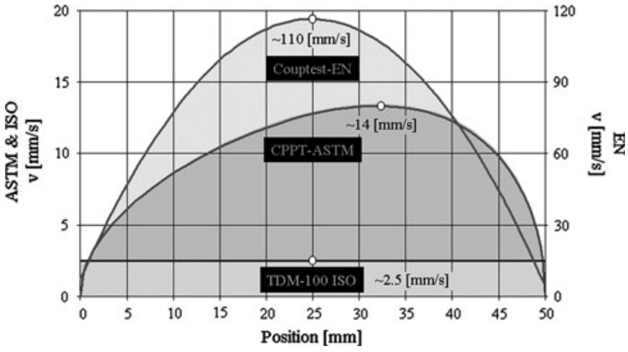


Fig. 3 Blade speed profiles: ASTM and EN is sinusoidal; and ISO is linear

harmonized distance). The corresponding load can reach, for knitted samples made of HCP fibers, the equivalent of 1000–3500 g, i.e., 10–35 N, which is 2–7 times higher than the load force applied on the circular blade in the case of the EN method. This is a difference worth highlighting.

As per Fig. 3, the blade displacements in the case of the ASTM and EN follow sinusoidal profiles with respective maximums of 14 and 110 mm/s. The ISO blade displacement profile is linear and fixed at 2.5 mm/s. A 40-fold ratio exists between the maximum 110 mm/s and the minimum 2.5 mm/s speeds. Here is another major difference, which is worth keeping in mind.

Cut performance can be and has been approached using various cut lengths before deciding on the finally "settled" harmonized length of 20 mm across the ISO–ASTM norms. The data corresponding to the 10-mm cut length, or less, remains valuable given the fact that the shorter the length, the closer the cut event gets to a puncture event.

We have, therefore, proposed to use a combined cut index [22, 23], combining the longer and the shorter cut length to discriminate material-specific cut behaviors. Although this approach is not at the center of our study, it is worthwhile to mention that the differentiation aspect, given the nonlinear cut response of most materials and the nature of the materials, is not relevant in the practical field.

To a certain extent, the study by Thang et al. [24] on the puncture resistance of rubber materials used in protective apparels, constitutes another basis to demonstrate the fact that an index combining several relevant mechanical performances as proposed by Rebouillat et al. [22, 23] would definitely bring value to the scientific and technology discussion forum.

Materials for calibration and testing

The calibration materials used for the ASTM and ISO methods differ from those used for the EN testing. Rubber is used for the former two, and textile for the EN. A key difference in the cut mechanism between the two reference materials may also be worth paying attention to, as shown on Figs. 4 [11, 12] and 5 [14], which will be discussed later.

For all the measurements performed in this study, the blades used, respectively, for the ASTM or ISO and EN tests are as follows:

-ASTM and ISO: Razor Blades 88-0121, type: GRU-GRU from American Safety Razor, USA

-EN: OLFA RB 45-mm circular blades from OLFA Corporation, Osaka, Japan

The neoprene reference material used for the ASTM and ISO testing: Neoprene 0.062 inches thick style NS-5550 from Fairprene, USA

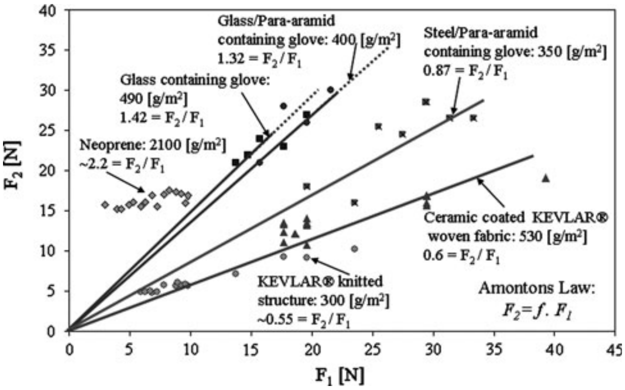


Fig. 4 F_2/F_1 ratios for various materials submitted to ASTM cut testing

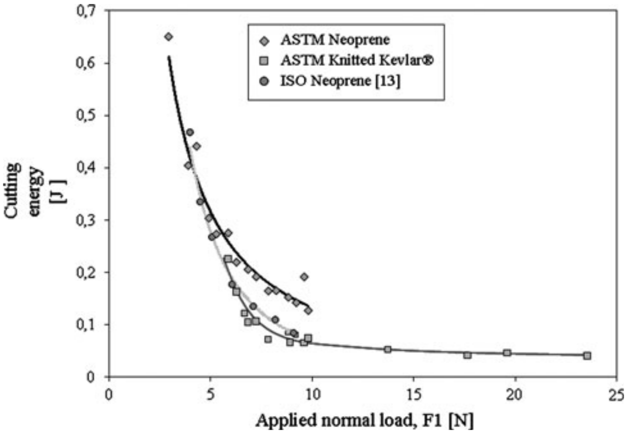


Fig. 5 ASTM/ISO sutting energy versus applied normal load

The cotton fabric reference material for the EN testing: 540 g/m^2 plain weave fabric of 1.2 mm thickness referred under: LEM 6 (cotton écru) from IFTH, Lyon, France.

The double-faced tape used to fasten the sample specimen onto the ASTM and ISO sample holder: Double-faced adhesive tape, 2 in. × 36 yd, type Kendall Polyken® #100D from Can-do National Tape, USA.

Tested materials

To start with, we may need to underline the "relevance" of the materials tested.

A significant amount of information has been compiled in [18] regarding high performance materials used in this study—especially aramids are covered by Rebouillat and Aramids [18], Rebouillat [25]. Earlier, cut resistance studies [9, 10, 13] have been focused on homogeneous materials such as elastomeric layers which exhibit relatively clear and controllable frictional behaviors and tear propagation mechanisms. The mechanical resistance of aramids is much more complex due to their intrinsic properties and structure formation during the spinning and coagulation event. Nonmeltable in characteristic, the aramid fibers are made of fibrids, fibrils, and filaments having a radially orientated gradient of composition and matter orientation; i.e., a relatively softer core with a harder skin structure hardness of which results in part from the post-spinning treatment. The well-known pleated internal structure of the para-aramid provides an entanglement which contributes to internal friction resistance and to breaking. The porosity of these materials and the variable, however, relatively modest, water content, can influence their mechanical behavior under multidirectional stress gradients. Finally, one cannot neglect the fact that those materials are knitted to manufacture protective layers. The interpretation of their cut resistance using a classical friction and tear model becomes challengeable; one shall carefully consider the high performance fibers' rather complex matter structure before attempting to use these classical models. The analysis of coated knitted materials renders the interpretation of the cut event simpler. Our objective remains to test commercially available protective materials using a scientific approach and equipment used for their specification. Fortunately, such equipments have been developed and validated as research tools as well [14, 15, 11]. The other materials used in this study are well covered in the literature; again let us be careful about relating their generally described properties with the fairly complex cut mechanism of those materials in knitted structures. The user community is looking for scientific guidance to interpret the three available types of normalized testing and this contribution from the guidance remains of paramount importance.

The majority of the materials tested in the course of this study are knitted fabrics from knitted gloves, mostly made of glass, steel, and para-aramid fibers such as Kevlar®.

The para-aramid fibers used are staple yarns of 0.0714 g/m produced from 38-mm long segmented fibers made from continuous filament yarns composed of about 1,000 filaments of 12-µm diameter with a specific density of 1.44 g/cm^3. Most para-aramid yarn samples were supplied by E.I. DuPont De Nemours Inc., Richmond, USA.

The steel fibers used in the study are commercially available single fibers of about 50-µm diameter with a specific weight of 7.85 g/cm^3 essentially made of food grade stainless steel 116.

The glass fibers used in the study are commercially available multifilament fibers of 0.0100–0.0200 g/m made of single filaments of about 6–8-µm diameter with a specific weight of 2.58 g/cm^3.

Relative values and typical strain versus stress relationships for para-aramid, glass, and steel are given in Fig. 6. The notation "dpf" stands for denier per filament. It is a weight-per-unit-length measure of a fiber material. It is equal to the weight in grams of 9000 meters of an

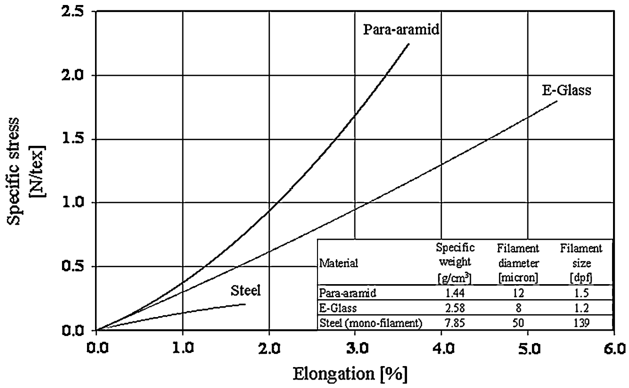


Fig. 6 Fiber stress–strain curves. Para-aramid, glass, and steel

individual continuous filament or an individual staple filament considering that it is continuous. The "tex" is the equivalent of the denier for a 10000 meters length used as reference.

Samples described as "glass containing glove" also generally contain a plurality of filling yarns such as cotton, polypropylenes, polyamides, polyesters, polyvinyl alcohol polymers…

Knitted samples and fiber assemblies

The specimen submitted to the cut testing, are samples mostly cut off gloves, as per the normalized sample preparation and guidance dictated by the testing methods [16, 20, 21].

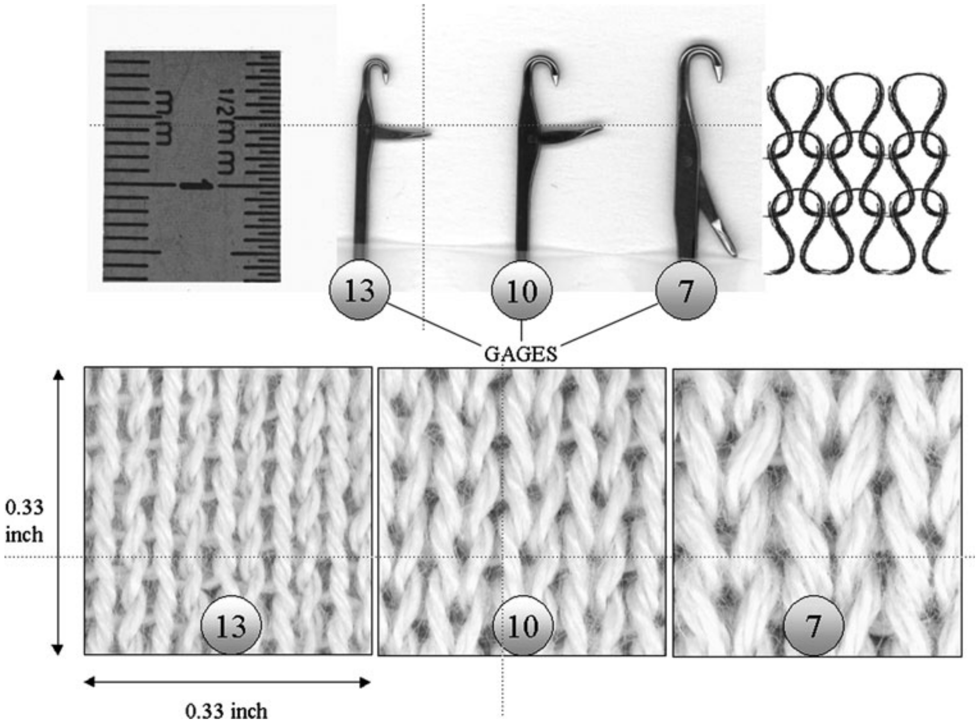
The knitting technology used in the making of gloves is beyond the scope of this article; nonetheless it is essential for subsequent data analysis to provide some knitting basics.

Knitting machinery are generally classified by a gage, which determines the thickness and therewith the specific weight, and areal density, of the knitted article. Articles of a given gage can be made of different sizes such as small, medium, or large without affecting the specific density and areal density associated with the selected gage.

It is essential to pay attention to the typical and rather unique fiber assembly of knitted structures, which are determinants in their "fracture" and make them a unique material, e.g., reinforcement of hoses or to make gloves. Those assemblies differ from woven plain fabrics mostly irrelevant in applications such as ballistic where the shock wave dissipation process away from the impact is of major relevance. Most studies tend to confuse those two types of material; moreover given that they can differ in their cut performance, but more importantly, in the cut mechanism, it is useful to illustrate how knitted structures are made.

Figure 7 provides several pictures of the knitted fabric patterns and the needle sizes corresponding to a given gage. The larger the gage, the smaller the specific weight and the areal density of the resulting knitted structure, and the smaller the needles that are used to make the corresponding fabrics or gloves. The schematic pattern of the yarn loop is shown in Fig. 7 as well, with the typical path of the yarn. Obviously, variations of that pattern are available while using other knitting machines. The smaller

Fig. 7 Typical interlocked knitted textile structures with various loop and node sequences pending on the gage sizes 7, 10, 13



gages produce larger loops, thereby more "aerated" and more open fabrics. The pattern density is largely associated with the number of needles per unit length, which provides the opportunity with larger gages to make less aerated knitted fabrics. Obviously larger needles will accommodate larger yarn thicknesses, which cannot be accommodated by smaller needles, and, therefore, generally the smaller the gage, the thicker the knitted fabric.

Most samples were knitted using glove-knitting machines from Shima Seiki Ltd., Sakata, Wakayama, Japan. Populations of samples have been selected keeping in mind the homogeneity factor such as the same process to make them, comparable average specific weights, etc. In general, samples correspond to "commercially" available or feasible knitted items to test populations which "make sense" in terms of their industrial representativeness and end-use suitability.

Yarn assemblies

Several yarns can be fed into the knitting machine to make smaller gaged fabrics out of multiple smaller yarn thicknesses. Multiple yarns can be fed in parallel without any prior twisting of the individual yarns together. In general and in most cases, all the separate components are twisted together before knitting. Flat yarns are rarely used directly in a traditional knitting machine. For knitted articles with a glass or a steel reinforcement, the steel filament or the glass yarn is a component of the yarn fed into the knitting machine. Such combinations are most of the time manufactured either by wrapping, twisting, spiraling, or intermingling. Figure 8 gives a few examples of combined para-aramid yarns with glass or steel fibers.

In Fig. 8, the fracture mechanism of a glass/para-aramid composition during the cut event is depicted and could be subject of a micro or nanoanalysis, which is not the focus of this study.

Material testing

Various knitted samples, described in Table 1, were tested, strictly reproducing the procedure described in each norm, including calibration of the equipment, preconditioning of the samples, and fixture of those on the sample holders. Those samples include various fabric areal densities and compositions selected in such a way as to best represent and to differentiate, the behavior of steel, glass, and para-aramid knitted fabrics.

All measurements represent an average of 45 cut tests in the case of the ISO method, and 15 cut tests for the EN method. Corresponding data are submitted to a Minitab® statistical processing for repeatability, reproducibility analysis, and the calculation of other more usual statistical parameters including normality test, variance, and mean analysis for differentiation.

Results and discussion

Preliminary considerations

As a preamble let us provide a few guiding considerations.

The cut mechanism and related fundamentals have been extensively reviewed in the dedicated section of the "Introduction". The large diversity of situations, where cut is involved, and the rather large number of physical phenomena superimposed in a cutting operation, render a detailed scientific approach much more difficult.

There are some qualitative reflection points, which may guide the "novice" and help the reader through this section.

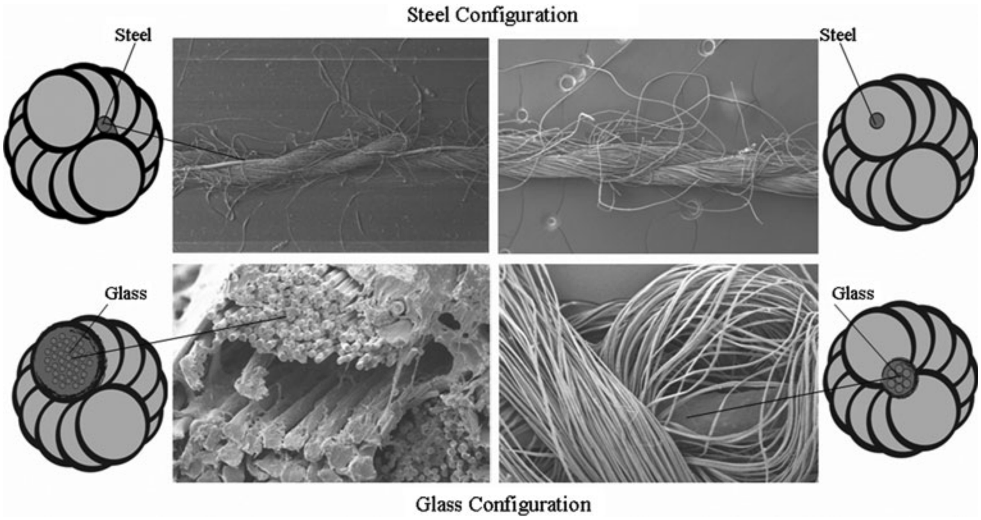


Fig. 8 Different yarn constructions and compositions and their SEM pictures (scanning electronic microscope)

Table 1 "Commercially" available or feasible knitted samples

	Conditioned weight (g/m^2)	Gage	Steel reinforced Mat (%)	Glass reinforced Mat (%)	Para-aramid (%)	Other man-made filler (%)	EN388 (index)	ISO NFl (N)
Para-aramid-containing glove								
Minimum	202	13	–	–	100	–	3	4
Maximum	1240	7	–	–	100	–	38	22
Average	507	–	–	–	100	–	8	10
Steel/para-aramid containing glove								
Minimum	236	13	6	–	94	–	11	18
Maximum	653	7	22	–	78	–	47	28
Average	412	–	12	–	88	–	24	23
Glass/para-aramid containing glove								
Minimum	265	13	–	8	92	–	12	10
Maximum	452	10	–	36	64	–	36	20
Average	376	–	–	14	86	–	21	13
Glass containing glove								
Minimum	280	13	–	6	–	94	10	9
Maximum	588	7	–	26	–	74	187	14
Average	443	–	–	18	–	82	92	11

Materials, which are generally considered as cut resistant materials, are also exhibiting

- a good tear resistance;
- a reasonable puncture resistance toward sharp but not too thin perforators;
- a certain resistance to abrasion or ability to fibrillate.

In the cutting process itself one may consider the following as useful considerations:

- the amount of material per unit volume, which the cutting threat or device has to go through.
- the deformability and the tendency for this material to maintain a high density under pressure still keeping its flexibility. Creep is also part of that aspect.
- the mobility of the fibers on which the blade is sliding. A revolving material or assembly being more difficult to cut.
- the blade dulling effect of the material being cut. Glass is a good example.
- toughness and resistance to the impact of the structure are also significant in the cutting sequence of events.

Fibers with skin–core structures are generally more protective. The thickness of the skin is a positive attribute; para-aramid fibers are high cut resistant.

Rather brittle materials tend to be less effective. On the other hand, ductility defined generally as the property of metal which permits it to be reduced in cross-sectional area without fracture, can be a good attribute. Steel and glass tend to support these two situations.

Furthermore, in order to put into context, the type of forces involved in such testing procedures one may consider the following:

The pressure applied by a blade of 1 mm^2 under a load force of 10 N, corresponds to a contact pressure of 10 MPa.

The above does not take into account the heat transfer and creep effect occurring during the application of a sudden localized pressure, for example, during abrasive wear or puncture of the materials.

Let us now consider the data obtained in this series of testing:

A global chart provided in Fig. 9 shows the relationship between the ISO testing and EN testing of various knitted samples made of para-aramid, glass, and steel-reinforced yarns.

Table 1 provides the characteristics of the sample tested. We have elected not to detail the results based on gage size to simplify the approach. The gage aspect will be discussed in more detail in an article under progress.

In Fig. 9, each point represents 45 cut tests for ISO and 15 cut tests for EN, representing a total amount of approximately 1890 single data measurements in case of ISO and 630 in case of EN. This sort of data analysis has never been reported.

For better comprehension, without extending the scope of this article, the EN index is calculated from the number of cycles, related to the number of wheel turns, necessary

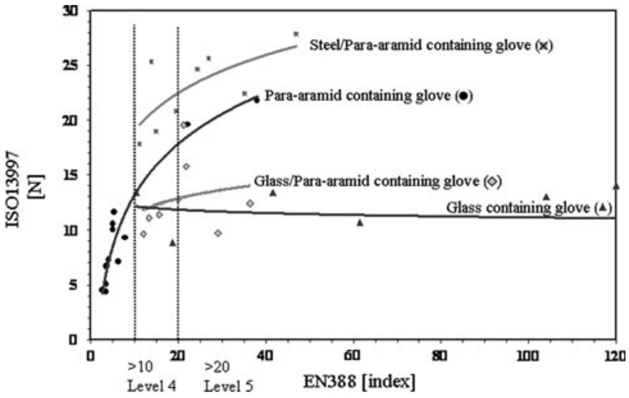


Fig. 9 Relationships between ISO13997 and EN388 for a series of HCP materials

to cut through the sample. References [11, 12, 16, 20, 21] provide the detailed calculations. The specific equation is as follows:

$$i_n = \frac{\bar{C}_n + T_n}{\bar{C}_n} \tag{1}$$

where i_n is the cut index given as a function of $\bar{C}_n$ and T_n. $\bar{C}_n$is the average value of, C_n, the blade cycles measured for the cotton reference materials before, and, C_{n+1}, the number of cycles after the testing of the test material performed with the same blade, and T_n is the number of cycles to cut trough the test sample.

Cut levels 4 and 5 are indicated in Fig. 9, since they represent, among a 5-level classification, the highest cut performance measurable with EN.

There are several findings to outline at a first glance of Fig. 9:

1. a flattening effect with the increase of the reinforcing fiber percentage, in the case of the testing of glove partitions containing a glass fiber-reinforced yarn. Lara et al. [19] anticipated that situation.
2. on the contrary, there is no flattening effect in the case of glove partitions containing a steel-reinforced yarn. An increase in the ISO load, necessary to cut through, is always backed-up by an increase in the number of EN cycles (wheel rotations) necessary to cut through the same sample.
3. the para-aramid samples, without any reinforcement, tend to follow the same trend as the steel-reinforced one.
4. glass/para-aramid mixtures lie between category 1 and 3 above with a flattening tendency as well.

One can benefit from assigning values corresponding to the extremes (min, max, and average) of each curve in Fig. 9 using Table 1, which provides the knitted fabric density and composition versus the performance, ISO, and EN, for each category being tested. Within the precision of the methods, there are no unexpected rankings; all increases of the knitted fabric specific weight or of the reinforcing element percentage, provide a higher ISO performance or a higher EN performance, or both. The predictability of the test methods tends to apply to both the specific density and the gage, which are directly interrelated. The specific density and the gage, and, the amount of reinforcing materials, whether being steel or glass, follow the same trend in terms of the resulting performance.

The "statistical meaning" of the collected data

MINITAB® statistical package was used to study the analysis of variance, based on the one-way ANOVA test as illustrated in Table 2, to determine the existence of differences among several population means. This, after a preliminary normality test based on Anderson–Darling method applied to each selected category. The Anderson–Darling test is an alternative to the chi-square and Kolmogorov–Smirnov goodness-of-fit tests.

The four populations being compared are: 1: para-aramid-containing glove, 2: steel/para-aramid-containing glove, 3: glass/para-aramid-containing glove, and 4: glass-containing glove. Cut test values as per EN and ISO standards are the data of interest. Some requirements should be met before the one-way ANOVA can be used for mean comparisons. They are

1. The population from which samples are drawn should be normally distributed. As shown in Table 2, the Anderson–Darling normality test provides, in all cases considered, a p-value higher than 0.05, which also supports normality.
2. The sample series should be independent of each other.
3. For the sake of homogeneity of analysis, the variance between the groups should be approximately equal.

All statistical analyses summarized in the Table 2 are comparing the various populations two by two based on a single treatment factor; then, this is considered as a one way ANOVA analysis.

The statistical analysis was performed with carefully selected representative groups of samples of each family to insure that all the sample groups contain samples knitted on the same gage at the same specific weights. Therefore, families were compared with consistency as follows:

1. the same material morphology, all material being in yarn form mostly cylindrical,
2. the same material configuration, all samples knitted on the same machine with the same loop density,
3. all the samples within the comparison groups have the same specific weight (g/m^2).

Table 2 One-Way ANOVA test on “Commercially” available or feasible knitted samples

Reference	Reference	Number of series	EN388 cut [index]		Anderson–Darling test normality *p*-value
			Average	Stdv	
1: Para-aramid-containing glove	1	17	8.5	9.5	0.154
2: Steel/para-aramid-containing glove	2	8	24.2	12.1	0.485
3: Glass/para-aramid-containing glove	3	8	21.2	8.2	0.484
4: Glass-containing glove	4	9	92.1	62.1	0.751

EN388 One-Way ANOVA test	Ref. (1 vs. 2)	Ref. (2 vs. 3)	Ref. (3 vs. 4)
P-value	0.002	0.57	0.006

Reference	Reference	Number of series	ISO cut Normalized force [N]		Anderson–Darling test normality *p*-value
			Average	Stdv	
1: Para-aramid containing glove	1	17	9.4	5.1	0.359
2: Steel/para -aramid containing glove	2	8	22.9	3.5	0.73
3: Glass/para-aramid containing glove	3	8	12.8	3.3	0.152
4: Glass containing glove	4	9	11.4	2.1	0.093

ISO 13 997 One-Way ANOVA test	Ref. (1 vs. 2)	Ref. (2 vs. 3)	Ref. (3 vs. 4)
p-value	0	0	0.295

The various series of products are, therefore, belonging to “homogeneous” and coherent populations.

This is very relevant with the fact that these gloves are selected, sold, and used mostly based on their compositions. The user in his/her selection and attempt to understand the cut differences and other performance differences will appreciate to know whether various families of product are statistically differentiated.

A few instances may help describe the findings:

Concerning EN cut tests, for reference (1) para-aramid containing glove and reference (2) steel/para-aramid containing glove, the One-Way ANOVA test provides a *p*-value of 0.002. The *p*-value is less than alpha (0.05), which is the maximum acceptable level of risk for rejecting a true null hypothesis. Then, we can conclude that the two sets of data are different.

A second example can be based on ISO cut performance. For the reference (3) glass/para-aramid-containing glove and the reference (4) glass-containing glove, the One-Way ANOVA test provides a *p*-value of 0.295. The *p*-value is higher than 0.05. Then, we can conclude based on ISO cut performance that the two sets are not different at a level of risk of 0.05.

In other words

- One cannot distinguish between, via EN testing, glass/para-aramid and steel/aramid-containing materials, but can do so via ISO testing in agreement with [19].
- On the other side, one cannot differentiate glass/para-aramid compositions versus glass-containing compositions via ISO testing but can do so via EN testing. It is important to underline that the CV for the two families are clearly substantially different, i.e., about 30% variability for the first one, and more than 60% variability for the second one.

The two examples discussed above do confirm the difficulty to test glass-containing materials via EN, the brittleness of glass which is the limiting factor in ISO testing, and the likelihood that the para-aramid reduces the variability of EN testing in the case of glass-containing compositions. This latter observation may imply that the para-aramid is contributing to making the cut performance less variable, thereby more predictable. The fact that para-aramid does not melt can also be an additional favorable attribute; most other fillers associated with glass are generally meltable, such as polypropylenes, polyamides, polyesters, polyvinyl alcohol polymers, etc. Let us note that, in these cases, the softening of the polymers may generate lateral and tip frictions. This situation would then be closer to the study reviewed in the “Introduction”.

In terms of variability as measured by CV, Lara et al. [19] did report large variability for this kind of testing.

The same line of reasoning can be applied for the other cases described in Table 2.

Forces involved during the cutting process $\|\vec{F}_2\|/\|\vec{F}_1\|$ ratio

The apparatus designed to measure the cut performance as per the ASTM procedure is shown in Fig. 10 along with a schematic diagram, which provides the blade orientation and displacement, and force application point. The sample position between the blade and the curve-shaped sample holder is well indicated. This force is generated by weights placed on a plate mounted on a lever arm assembly in such a way that doubles the resulting force applied to the specimen. The test apparatus also consists of a motor-driven balanced arm, which holds the blade.

In order to measure the co-linear force component offering resistance to the displacement of the blade, a 50-N (or 200-N) load cell, type S2 from HBM Germany, was installed in the arm holding the blade as shown in Fig. 10. Connected to a computer interface, module MP55 from HBM Germany, the resisting force, $-\|\vec{F}_2\|$, was recorded during the cutting process using the CATMAN® software from HBM Germany. The normal force, $\|\vec{F}_1\|$, applied onto the blade edge is assumed to be directly proportional to the double weight force value, which is an approximation, since during the displacement and due to the thickness of the sample, the blade cutting edge does not remain strictly perpendicular to the direction defined by the sample holder center and the sample contacting point at a fixed time. This is depicted in Figs. 10 and 3.

Thi et al. [14] has instrumented the TDM-100 (ISO 13997) to measure simultaneously the applied normal load and the horizontal force resulting from the sliding movement of the blade at different speeds ranging. Let us underline that the blade speed in the TDM-100 ISO situation is much smaller than in the CPPT ASTM case, as indicated in Fig. 3.

The force $\|\vec{F}_2\|/\|\vec{F}_1\|$ ratios of all classes of HCP materials, aramid, steel, glass, and rubber, have been summarized in Fig. 4. Rubber has been added to the curve, since it is not only used for calibration but also for its singular properties in terms of elasticity versus glass. The cut behavior of elastomers is well described and fully developed by Lake and Yeoh [9], Cho and Lee [13]. Figure 5 provides the ASTM/ISO cut energy versus the normal applied load for the neoprene elastomer 1.57-mm thick sample [14] and a knitted Kevlar® sample. ISO/TDM 100 and ASTM/CPPT overlap in the lower range of the normal load, and then differ since cutting speed has a significant impact on the cut mechanism, especially when frictions are involved. As specified in [14], the ISO test cut speed was run at the normal testing value of 2.5 mm/s which is about five times lower than that of the ASTM one. The mandrel supporting the sample and the arm supporting the blade also yield a slightly different contacting point configuration in the two latter cases, ISO vs ASTM.

During the cut process, the sample containing glass as well as the samples made of rubber exhibit high resistance to the displacement of the blade followed by steel and para-aramid. Ceramic coated Kevlar® woven fabric is provided in Fig. 4 as a reference, not further explored in this study. This reference tends to show lower performance of those fabrics generally lighter than knitted structure, although the ceramic coating adds substantial mass to the substrate.

For the neoprene calibration material the resisting force, $-\|\vec{F}_2\|$, is about 2.2 times superior to the normal applied

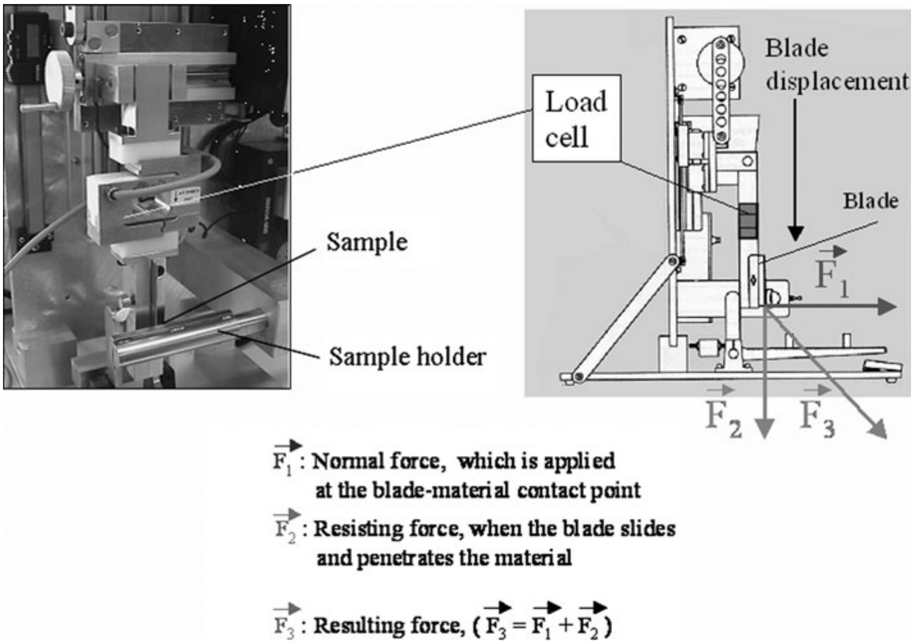


Fig. 10 CPPT (ASTM) equipped with a compressive load cell

force, $\|\vec{F}_1\|$. The resisting force found in this study is almost equal to the one, identified as a frictional force, reported by Massé et al. [7]. Therefore, our findings, although conducted independently on a different testing apparatus, ASTM versus ISO, are fully in line with the study conducted by Lara and Massé [26] at the IRSST, Québec Canada. This is a good demonstration of the interchangeableness of the two equipments now both recommended in the ASTM norm. Thi et al. [15] also presented similar cutting forces distribution in the case of the study of neoprene 1.57 mm and the Kevlar®.

Rubber behaves differently relative to glass since a threshold can be identified. The use of the Amontons' law for that latter case is difficult and necessitates a more in-depth study. Nonetheless, one can conceive that the density of the material as well as its intrinsic elasticity are contributing ward resistance to the displacement, which does not diminish at the onset and during the cutting process since intrinsic antagonistic-related forces are maintained and constitute high frictions as indicated in the reviewed studies.

The glass material submitted to relatively low forces will not break but will contribute to the dulling of the blade edge, more precisely in the case of the EN testing where the circular blade contact with the sample are repeated. Under higher forces, during ASTM test, the glass material may break and abrade leading to glass dust and surface roughness capable to prevent the blade movement. Therefore, the higher friction observed for glass during the ASTM test is represented in Fig. 4.

Figure 8 also depicts the type of fracture mechanism during the cut of a glass/para-aramid composition. A micro or nanoanalysis of the cut-fragmented pattern confirms the above.

Figure 4 also provides the $\|\vec{F}_2\|/\|\vec{F}_1\|$ ratio for a para-aramid-knitted structure and a ceramic-coated Kevlar® woven fabric. The two ratios are more or less one-fourth of the neoprene measured ratio. Without questioning the suitability of using such a material as a calibration material, one can underline that the blade sharpness uniformity is tested against a very different material relative to the samples tested, except for coated textiles. This can have advantages and disadvantages. The EN still refers to a cotton reference. This matter is beyond the scope of this study.

Furthermore, the amount of friction generated to cut through neoprene may explain why a dotted knitted structure exhibits an artificially high cut EN performance.

The necessity to use the blade cutting edge only once during a test is essential in a situation where abrasions of the surface of the tested material are high.

Steel-containing materials stay between glass and para-aramids possibly because of its continuous form, reducing the mobility or possibly provoking entanglement with the blade. The ductile nature of stainless steel is also a criterion in favor of a retarded higher cut through since the material tends to thin down in section before cut. The metal-to-metal contact between the blade and the reinforcing stainless steel material can also contribute. The presence of para-aramid in the steel-containing compositions may explain its position in between glass and para-aramid which may be reducing, to a certain extent, the gliding effect due to friction.

For the sake of completeness, it is necessary to mention that heat dissipation has an effect on the resistance ratio described above. The use of meltable fillers, polypropylenes, polyamides, polyesters, polyvinyl alcohol polymers etc., can induce an additional friction contribution. The effect of temperature on cutting resistance is well described by Gent [10].

From those observations, both in terms of EN and ISO cut performance or force distribution during the cut event, a more in-depth discussion could take place regarding the association of HCP materials: composition wise as well as in terms of configuration or position—core or wrapping protecting sleeves.

Newly developed multi-dpf structures [23] would also be valuable to this kind of fundamental understanding given their higher end-use performance.

Given its brittle structure, a coating of glass fibers with rubber could be beneficial to retarding the cut sequence by reducing the speed and the impact of the cutting edge.

Steel cannot be used at 100% for processing reasons as well as comfort, risk of puncture, and weight; it, therefore, makes sense to associate steel with para-aramids as a wrapping high cut resistant sleeve. Furthermore, the para-aramid does not melt thereby buffering any local heat increase. It would not make as much sense to associate glass and steel in any configuration.

Ceramic coatings are going to bring, pending on the resilience of the core element, an interesting dulling effect without reducing the core energy dissipation potential.

Given that the EN cut corresponds more dominantly to an "abrasive" cut, a wear-like phenomenon, and which ISO relates more to a "forced penetration" cut, one can favorably use the data provided in this article to associate cut measurement and force distribution during the cut event, to tailor compositions and derive a more universal protection.

It may also appear, although not being the focus of this article, that the par-aramid is a better companion to glass and steel than usual fillers such as cotton, polypropylenes, polyamides, polyesters, polyvinyl alcohol polymers, etc. In a study, made by Van Dingenen [27], which includes a rather "generically" drawn figure of various cut behaviors, the above seems to be confirmed since, for a given range of gages, specific densities, or areal densities, steel and glass do not appear to bring the same synergism with those fillers as the one observed in the case of para-aramid [28]. A more detailed analysis of more specific examples would really be necessary to consolidate this aspect.

Conclusion

Three essential reinforcing materials, steel, glass, and para-aramid, have been compared using methods known in the art testing, mainly cut testing.

(A) The associations in composite forms of those materials reveal synergism that may be translated into the manufacturing of protective equipment. Glass and rubber are generally associated and used in fatigue-demanding applications; can they also be associated in cut resistant application? Para-aramids are key HCP reinforcing elements but can also become companions of other reinforcing elements that can not be used alone, such as glass and steel? In such cases, what shall be the optimized configurations and compositions to meet a specified cut performance? Peripheral or core or combined? Our study brings some answers which may deserve further analysis.

(B) The instrumentation of classical testing device brings a new dimension to the testing performed to meet specifications while adding a more fundamental comprehension of the testing boundaries as well as the material intrinsic properties. This opens a new era of testing where fundamental science and technology can merge to form the “fundamental applied understanding scheme” necessary to meet today’s requirements in terms of performance and safety. For example, the glass brittleness has been confirmed as a limiting factor for puncture-like cut events while helping to maintain a certain level of abrasive resistance in the case of wear-like cut. Rubberized glass might be a route to reconsider in other applications.

(C) The selection of homogeneous samples, “commercially” available or feasible, further supports the above statement as long as those populations are tested for their statistical significance. For example, glass-containing samples may be improved in terms of variability by adding para-aramid to their compositions.

In this article, other physical properties of reinforcing elements and their companions have not been fully investigated. The meltability of the companion yarns would deserve more attention.

The resilience of the materials studied can be recognized with a different angle. Although stainless steel cannot be used at 100% to manufacture high dexterity gloves, it may be, at a much lower concentration, the ideal companion to meet extreme cut resistance levels. Data provided in this study support this aspect unequivocally using ASTM, ISO, and EN standards. This is not the case for glass-reinforced materials for which the three standards do not provide homogeneous responses, due to the intrinsic properties of this material. These results should not be unduly extrapolated beyond the test methods used in this study without conducting more testing methods in the specific situations of interest.

A large amount of study remains to be done to fully integrate all the components of the identified improvement in the global understanding of how the cut mechanism and testing can evolve to be better predictive tools for the material science approach.

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References

1. Dias JJ, Garcia-Elias M (2006) Injury 37(11):1071
2. Sorock GS, Lombardi DA, Courtney TK, Cotnam JP, Mittleman MA (2001) Saf Sci 38(3):241
3. Cheng YH (1997) Soc Sci Med 45(5):739
4. Gustafsson M, Ahlström G (2006) Int J Nurs Stud 43(5):557
5. Tejani N, Blocker R, Schiffelbein P, Rivet E (1997) In: Stull JO, Schwope AD (eds) Performance of protective clothing: sixth volume, ASTM STP 1273. American Society for Testing and Materials, p 84
6. Lara J, Turcot D, Daigle R, Boutin J (1996) In: Johnson JS, Mansdorf SZ (eds) Performance of protective clothing: fifth volume, ASTM STP 1237. American Society for Testing and Materials, p 23
7. Massé S, Lara J, Sirard C, Daigle R (1997) In: Stull JO, Schwope AD (eds) Performance of protective clothing: sixth volume, ASTM STP 1273. American Society for Testing and Materials, pp 66–83
8. Yarborough P, Schiffelbein P (2005) In: Yarborough P, Nelson CN (eds) Performance of protective clothing, Revisions to ASTM F 1790. p 134 (ISBN 0 8031 3488 6)
9. Lake J-G, Yeoh HO (1978) Int J Fract 14(5):509
10. Gent NA, Wang C (1996) J Polym Sci B 34:2231
11. Rebouillat S, Steffenino B (2005) In: Yarborough P, Nelson CN (eds) Performance of protective clothing. p 139 (ISBN 0 8031 3488 6)
12. Rebouillat S, Steffenino B (2006) In: Brebbia CA (ed) High performance structures and materials, vol III. WIT Press, p 279 (ISBN 1 84564 162 0)
13. Cho K, Lee D (1997) J Polym Sci B 36:1283
14. Thi VNB, Khanh VT, Lara J (2005) J Thermoplastic Compos Mater 18:23
15. Thi VNB, Khanh VT, Lara J (2009) Theor Appl Fract Mech 52(1):7
16. ISO13997, ISO/TC 94/SC 13/WG 5N 173, Protective clothing–mechanical properties–determination of resistance to cutting by sharp objects

17. Thi VNB, Khanh VT, Lara J (2005) In: Yarborough P, Nelson CN (eds) Performance of protective clothing. p 160 (ISBN 0 8031 3488 6)
18. Rebouillat S, Aramids (2001) In: Hearle JWS (ed) High performance fibres. Woodhead Publishing Limited, Abington, Cambridge, p 23 (ISBN 1 85573 539 3)
19. Lara J, Turcot D, Daigle R, Payot F (1996) In: Johnson JS, Mansdorf SZ (eds) Performance of protective clothing: fifth volume, ASTM STP 1237. American Society for Testing and Materials, p 32
20. ASTM F1790-97, Standard test method for measuring cut resistance of materials used in protective clothing
21. BS EN388 (2003) Protective gloves against mechanical risks
22. Rebouillat S, Steffenino B, Miret-Casas A US patent US2004011087
23. Rebouillat S, Moore SD, Steffenino B, WO/2008/045492, Cut-resistant yarns and method of manufacture
24. Nguyen TT, Khanh VT, Lara J (2005) In: Yarborough P, Nelson CN (eds) Performance of protective clothing. p 175 (ISBN 0 8031 3488 6)
25. Rebouillat S (1998) J Mater Sci 33(13):3293. doi:10.1023/A:1013225027778
26. Lara J, Massé S Evaluating the cutting resistance of protective clothing materials IRSST, p 145
27. Van Dingenen JLJ (2001) In: Hearle JWS (ed) High performance fibres. Woodhead Publishing Limited, p 62 (ISBN 1 85573 539 3)
28. American National Standard for Hand Protection Selection Criteria ANSI/ISEA 105-2000