Development of Flexible Stab-proof Textiles Impregnated with Microscopic Particles

Bao Limin *, SATO Shunsuke, WANG Yaling, WAKATSUKI Kaoru, MORIKAWA Hideaki

Faculty of Textile Science and Technology, Shinshu University, 3-15-1 Tokida, Ueda, Nagano 386-8567, Japan

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Abstract

Most stab-proof vests in use are made from metal plates, whose weight, bulk, and rigidity make them unsuitable for use over extended periods of time. Light, thin, and flexible clothing that protects against knives and other sharp objects is needed. However, achieving high levels of puncture resistance and comfort remains a challenge. While plain textiles can resist slashing, they cannot withstand stabbing. In this study, we investigated the stab resistance of aramid fabrics impregnated with micro-glass particles and nano-silica particles and evaluated the influence of particle size and mass concentration by measuring the load, displacement, and energy when the samples were struck by a blade. Particle-impregnated fabrics showed good puncture resistance. The smaller the diameter of the particles, the greater the material’s resistance to penetration. Movement of yarn strands is inhibited by impregnation with particles. Furthermore, the friction force acting on intersecting sections of plain fabric exhibits the largest influence on stab resistance.

Key Words: Flexible textiles, Microscopic particles, Nano-particle, Stab-proof, Composite

1. Introduction

Police officers and security guards who must contend with the possibility of being unexpectedly attacked with a blade require flexible, low-cost textile protective clothing that affords a high level of stab resistance. As a result of the Act for Controlling the Possession of Firearms or Swords and Other Such Weapons, more crimes are committed with weapons such as ice picks than with guns or blades. Although stab-proof textiles are fairly effective against stabbing with a knife due to their use of high-strength fibers, they are less effective against objects such as an ice pick. When stabbed with an ice pick, the fibers near the encroaching point move away to create an increasingly large opening, allowing the pick to readily penetrate the material [1]. Efforts to develop a stab-proof material that affords a high level of protection against stabbing motion by an implement such as an ice pick are attracting attention. To date, we have pursued the approach of impregnating fabrics that have a large cover factor with elastomers to “lock” the yarn in place as a way of boosting stab resistance [2]. We have proposed a non-woven fabric structure that consists of dense, randomly positioned fibers as a low-cost, stab-proof material, and the advantages of that structure have been verified [1].

The literature also includes reports indicating that the phenomenon of dilatancy can be utilized to increase the ability of protective clothing perfused with dilatant fluid (STF) using nano-silica particles to protect against bullets and other projectiles [3-5]. However, we believe that further study is needed in order to determine whether the phenomenon is effective against low-speed stabbing motion with a weapon such as a knife.

In this study, we built on a previous paper by implanting microscopic particles into a textile material and investigated the

* Corresponding author: E-mail : baolimin@shinshu-u.ac.jp, Tel : +81-268-215423
potential for improving the stab-proof properties that protect against low-speed stabbing motion (Fig. 1). We explored the associated mechanisms of penetration resistance and studied various influencing factors.

2. Samples of stab-proof material and their preparation

2.1 Materials

We used Kevlar fabric that is typically used as a stab-proof material (800T-490, Matsubun Textile Co., Ltd., K, Para-aramid fiber). The warp and weft density were 29 and 31 threads/inch, respectively, and fabric thickness was 0.4mm. The yarn thickness was 880 dtex.

We used spherical silica particles (QSG-30, Shin-Etsu Chemical Co., Ltd.) with an average diameter of 35 nm as the nano-particles for implantation, and we used hard, low-cost glass particles (UB, Union Co., Ltd.) with average diameters of 4, 6, 10, 20, 100, 500, and 900 μm as the micro-particles for implantation. We treated the surface of the particles so that they would adhere more readily to silicone rubber.

2.2 Production method for samples

The particles were kneaded into silicone rubber, and the samples were impregnated with the mixture. Two-part heat-cured adhesive liquid silicone rubber (TSE3331, Momentive Performance Materials Worldwide Inc.) was used as the silicone rubber. The material had a density of 1.51 g/cm³ and a hardness (Type A, JIS K 6253) of 60.

We mixed the curing agent with the liquid silicone rubber base and stirred them together. Then we added micro-particles or nano-particles and subjected the mixture to stirring and defoaming with a non-bubbling kneader (NBK-1, Nihonseiki Kaisha Ltd.) (2,000 rpm, 3 min.). Fig. 2 provides an overview of this process. We have expressed the ratio of the weight of the particles to the weight of the particle-silicone rubber mixture as a percentage (wt%). For example, a sample containing 50% particles with a diameter of 10 μm by weight would be indicated as “+10 μm, 50 wt%.” Using the hand lay-up method, we prepared the samples by impregnating Kevlar fabric with the mixture and cured it using a hot press at a pressure of 10 MPa and a temperature of 150°C for 1 hour. For the sample’s lamination structure, we impregnated four Kevlar fabric layers with the particle-silicone rubber mixture using the hand lay-up method to create a cast sample that we dubbed “(KKKK)q” using the method that we proposed in a previous paper [2]. To reduce flexural rigidity, we proposed the following molding method: we mixed 33 wt% toluene with the particle-silicone

Fig. 2 Overview of sample production.
rubber mixture, impregnated one Kevlar fabric layer with it, and evaporated the toluene at 70°C. We then cured the sample using a hot press at a pressure of 10 MPa and a temperature of 150°C for 1 hour. Finally, we stacked four of these samples together as shown in Fig. 3 and sewed their ends together in a simple manner with nylon filament to create a sample that we dubbed "(Kq)4." Four-layer fabric samples created using the lamination method we’ve used in the past we dubbed “KKKK.”

Fig. 4 provides photomicrographs of the surface of samples prepared using two lamination methods. The samples prepared using our proposed lamination method have a large amount of silicone rubber on their yarn to prevent movement of the fibers, but the material is expected to retain its flexibility as the method leaves less silicone rubber between individual strands of yarn than the method used previously.

3. Flexural properties of stab-proof materials

A stab-proof material must provide a certain amount of flexibility. To facilitate a quantitative evaluation of flexibility, we evaluated the flexural rigidity of the material, which is closely related to clothing flexibility. We used a pure-bending tester (KES FB2-L, Kato Tech Co., Ltd.) to conduct a pure-bending test and calculated the material’s flexural rigidity for curvatures ranging from 0.1 to 0.3 cm\(^{-1}\). We used 10 samples for each structure, each with a size of 200 mm × 200 mm.

Fig. 5 illustrates results obtained by testing the flexural rigidity of the KKKK(2.43×10\(^{-6}\)Nm\(^2\)), (KKKK)q(5.34×10\(^{-6}\)Nm\(^2\)), and (Kq)4 (351×10\(^{-6}\)Nm\(^2\)) samples, which had different lamination structures. As Fig. 5 shows, the flexural rigidity of the (KKKK)q samples, which were impregnated with silicone rubber, was dramatically higher than the KKKK samples, which consisted solely of overlapping fabric, leading to concerns that the material’s flexibility had been lost. By contrast, the (Kq)4 samples yielded flexural rigidity values that were considerably lower than those of the (KKKK)q samples and exhibited about the same level of softness as the KKKK samples, affirming the effectiveness of our proposed lamination method as a way to increase flexibility. These results derive from the fact that the cross-sectional second moment of area of the (Kq)4 samples, in which layers are overlapped after impregnation as per our newly proposed method, was 4\(^2\) times smaller than that of the (KKKK)q samples.

Fig. 6 illustrates the results of measuring the flexural rigidity of samples that were created by impregnating the (Kq)4 lamination structure with spherical glass particles (particle diameter: 4 and 20 μm, 33 wt%). Impregnating the samples with particles caused their flexural rigidity to increase slightly, with smaller particle diameters resulting in larger increases in rigidity. Microscopic examination of cross-sections of the particle-impregnated samples revealed that particles with smaller diameters were able to more readily penetrate the fabric yarn, hindering movement of the fibers and increasing the hardness of the sample, leading to increased flexural rigidity.

4. Effects of particles on stab-proof performance

Using a stab resistance evaluation device [1] that we had developed based on the U.S. standard for evaluating stab resistance (NIJ Standard -0115.00) in order to measure maximum load and penetration energy (When stabbing, the energy required to penetrate the sample) during stabbing, we evaluated the samples’ stab-proof performance.

Fig. 7 illustrates the stab-proof performance of each laminated structure. As shown in our previous report [2], the (KKKK)q structure impregnated with silicone rubber exhibited greater maximum load and penetration energy than the KKKK structure,
which consisted of four layers of fabric, indicating a high level of stab-proof performance. The stab-proof properties of the newly proposed \((Kq)^4\) structure were somewhat inferior to those of the \((KKKK)^q\) structure, with the former yielding readings of approximately 85% to 90% of those of the latter. We will use primarily the \((Kq)^4\) structure, which delivers about the same level of stab-proof properties despite having dramatically higher sample flexibility, in future study and tests.

We mixed glass particles with average diameters of 4 μm, 6 μm, 10 μm, 20 μm, 100 μm, 500 μm, and 900 μm with silicone rubber and impregnated Kevlar fabric with the resulting mixtures. Fig. 8 illustrates the penetration energy as measured for each sample. The particle concentration was 33 wt%. The addition of particles improved the samples’ stab-proof properties, with smaller particle diameters resulting in larger penetration energy values. However, excessively large particle diameters (for example, 900 μm) caused the associated penetration energy value to fall below the value of the original \((Kq)^4\) structure. Microscopic examination of the sample surfaces and cross-sections revealed that larger diameters prevented the particles from penetrating the yarn. As a result, the particles were concentrated on the surface of the sample, where they failed to improve the stab-proof properties.

We tried mixing nano-silica particles with silicone rubber and impregnating Kevlar fabric with the resulting mixtures. The nano-particles’ large surface area made it difficult to disperse them at high concentrations in the silicone rubber. We then evaluated the stab-proof performance of samples in which a uniform dispersion was achieved. Fig. 9 provides one example of those measurements for samples to which nano-silica particles were added at concentrations of 1, 3, and 5 wt%. The implantation of nano-particles caused penetration energy values to increase, and the increase was significantly greater than for micro-particles at the same concentration. The addition of nano-particles provides an effective way to increase protective performance against projectiles such as high-speed bullets\(^3\)-\(^5\), and these findings indicate that the technique is also effective for increasing protective performance against a low-speed attack with a blade.

We made measurements using two particle diameters (10 and 100 μm) to gauge the effects of particle concentration. Fig. 10 illustrates those results. As shown in the figure, higher particle concentrations resulted in higher penetration energy. Smaller particle diameters resulted in significantly higher levels of penetration energy. Penetration energy grows substantially as particle diameter decreases. However, the maximum concentration at which particles can be added uniformly falls as the diameter decreases. In this way, the increase in penetration energy is limited.

**5. How particle impregnation improves stab resistance**

As shown in Fig.11, we propose that there are two mechanisms by which particle impregnation increases stab resistance. The black arrows in the figure indicate stabbing force, while the red arrows indicate the reaction forces from particles. First, the trajectory of the penetrating spike is obstructed by the impregnated particles (Mechanism ① in Fig. 11). This phenomenon is a result of dilatancy\(^3\)-\(^5\). Second, the particles increase the friction force acting on intersecting strands of yarn (Mechanism ② in Fig. 11).

We then conducted an experiment to demonstrate the mechanism underlying this behavior. As described in Section 2.2, we kneaded glass particles into the material. We then formed the silicone into a sheet with a thickness of 2 mm. Fig. 12 illustrates the effects of collision speed on rubber samples’ stab properties. The particle density was 33 wt%. As shown in the figure, the addition
of particles caused the stab-proof properties to improve. The maximum penetration load also increased as the collision speed rose. However, the percentage increase in stab-proof properties for the samples in which particles had been implanted was about the same as for rubber alone.

Fig. 13 illustrates stab test results for silicone sheets with particle densities of 33 wt% and 66 wt%. While the implantation of particles resulted in an increase of stab-proof performance, particle diameter had no effect on the fabric samples (Fig. 8), providing confirmation of Mechanism ① explained in Fig. 11.

Fig. 12 Effect of collision speed on rubber samples’ stab properties.

Fig. 13 Effect of particle size on the stab-proof performance of rubber sheets.

Fig. 14 Test apparatus for measuring friction force of orthogonal yarn strands.

Based on these results, the increase in the material’s stab-proof performance gained by adding particles, including for low-speed stabbing motion, occurs due to the increase in friction between yarn strands and the attendant constraints on the movement of adjacent strands.

Based on the reason for the improvement in performance described above, we hypothesized that spherical particles constrain the movement of edge particles (particles of indeterminate shape),

JIS K 7125 (“Plastics—Film and sheeting—Determination of the coefficients of friction”) [6], we juxtaposed strands of yarn that had been impregnated with particles so that they intersected one another at a right angle and measured the friction force. Fig. 14 illustrates the measurement apparatus that we used to do so. We impregnated Kevlar yarn with silicone rubber that had been mixed with particles using the process described in Section 2.2 (“KYq”) and cured it on a sample pedestal. We also prepared a sample of silicone rubber that had not been impregnated with particles (“KY”). The vertical pressure was 0.5 kPa, and the contact area was 0.4 m².

Fig. 15 illustrates our friction force measurement results. Impregnating the silicone rubber with particles increased the friction force acting between the strands of yarn in the KYq sample compared to the KY sample. In addition, we found that smaller particle diameters resulted in greater friction force. That trend is the same as that illustrated in Fig. 8.

Based on these results, the increase in the material’s stab-proof performance gained by adding particles, including for low-speed stabbing motion, occurs due to the increase in friction between yarn strands and the attendant constraints on the movement of adjacent strands.

Based on the reason for the improvement in performance described above, we hypothesized that spherical particles constrain the movement of edge particles (particles of indeterminate shape),
increasing friction drag and stabbing resistance. We tried adding glass particles of indeterminate shape to test this hypothesis.

We added glass micro-particles of indeterminate shape (UP, Union Co., Ltd.) with average diameters of 6, 20, and 100 μm. The method used to add the particles to the samples was the same as that described in Section 2.

Fig. 15 provides a series of example friction force measurements, which were somewhat greater than for the spherical particles. Fig. 16 illustrates penetration energy as measured, which was greater for samples to which 20 μm and 100 μm edge particles were added than for spherical particles, indicating improved stab-proof properties. However, the penetration energy for the sample to which 6 μm particles had been added was about the same as for spherical particles, and no significant difference could be discerned. Fig. 17 provides an SEM micrograph of spherical and edge glass particles. Due to the method by which glass particles are manufactured, larger particle diameters are associated with more conspicuous edges, making them more likely to hinder movement of the yarn. Based on these results, we were able to verify our proposed mechanism in which the addition of particles improves stab-proof properties.

6. Conclusion

In an effort to create a lightweight, flexible stab-proof material with high stab-proof performance, we added microscopic particles to a textile stab-proof material and verified the effectiveness of the resulting material in protecting against stabbing attacks.

Impregnating material with microscopic particles improved stab-proof performance. Smaller particle diameters resulted in greater increases in stab-proof performance, as did higher particle concentrations.

Based on the results of a verification experiment in which fabrics were impregnated with particles, we were able to verify the mechanism responsible for increased stab-proof performance: the particles increased friction drag, constraining movement of yarn strands and increasing stab-proof performance.

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