

New protective clothing materials for working with handheld ultra-high-pressure water jet guns

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ABSTRACT

In many applications, hand-held water spray systems are replacing sandblasting as a cost effective and environmentally friendly alternative. In addition, waterjet technology offers new solutions for cleaning surfaces in difficult or confined spaces where sandblasting is virtually impossible. While operations in the manufacturing process are automated, water blasting requires the worker to operate a lance or spray gun by hand. Such hand-held high-pressure and ultra-high-pressure water jet lances operate at pressures of up to 3,000 bar.

Due to the international lack of suitable protective clothing systems, in particular for the use of water jet lances with round jet nozzle with pressures > 500 bar, the objectives of the project were 1) the development of protectors (knee and shin protectors, gaiters, aprons) based on metallic platelet structures, which should provide effective protection against punctual sources with pressures of at least 1,550 bar when using round jet nozzle and 2) the development of a technology for sewing on the platelet structures, in particular an automatic feeding of the plates on an automatic button sewing machine.

Keywords

waterjet, personal protective
equipment, scale-like structure,
protector

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1 Introduction

In many applications, hand-held waterjet systems are replacing sandblasting as a cost effective and environmentally friendly alternative. In addition, waterjet technology provides novel solutions for cleaning surfaces in difficult or confined spaces where sandblasting is virtually impractical. Although the manufacturing process itself is automated, water blasting requires the operator to handle a lance or spray gun manually. Such hand-held high-pressure and ultra-high-pressure water spray guns operate at pressures of up to 3,000 bar.

Hand-held water blasting results in wet and slippery working conditions as well as poor visibility due to spray mist. According to accident statistics from the German Social Accident Insurance (DGUV), an annual average of approximately 280 reportable occupational accidents involving high-pressure water cleaners occurred during the reporting period from 2010 to 2019. These incidents included accidents causing very severe injuries as well as one fatal accident [1].

Typical injuries include water jets penetrating footwear and feet, as well as the injection of contaminated fluids into the lower legs and thighs, torso, hands, and forearms; in some cases, serious injuries to the posterior regions of the body have also been reported. Some of these injuries can be fatal.

Currently, three protective clothing systems are available on the market: TurtleSkin® WaterArmor from Warwick Mills, Inc., USA, protective clothing from TST SWEDEN AB, Sweden, and DEHNcare® WJP from DEHN SE, Germany. However: none of these protective clothing provides sufficient protection against ultra-high-pressure application > 1,000 bar (especially round jet nozzles).

Owing to the international lack of suitable protective clothing systems – especially for waterjet lances equipped with round jet nozzles operating at pressures above 500 bar – the objectives of this project were 1) to develop protectors based on metallic platelet structures capable of providing effective protection against point-like waterjet impacts at pressures of at least 1,550 bar when using round jet nozzles and 2) to develop a technology for sewing on the platelet structures, in particular an automatic feeding of the platelets on an automatic button sewing machine. The protectors are intended to ensure unrestricted mobility and sufficient flexibility, and may be designed as knee and shin protectors, gaiters and aprons. The mass per unit area of the overall system, including waterproof protective covers, should not exceed 900 g/m².

2 State of the art

2.1 Description of initial situation and market need

2.1.1 Fields of application of hand-held high-pressure water jetting systems

While many operating areas are automated, water jetting requires the worker to guide a lance or spray gun by hand. In water jetting, two pressure ranges are distinguished [2, 3]:

- High-pressure (HP) water jetting: pressure 680–1,700 bar at flow rates of approximately 20 l/min,
- Ultra-high-pressure (UHP) water jetting: pressure > 1,700 bar at flow rates of 50–60 l/min.

The application areas for hand-held HD and UHD water jet lances are summarized below.

- Cold and hot water high-pressure cleaners with pressures up to 800 bar, see Figure 1:
 - removal of paint layers,
 - removal of coatings and corrosion protection systems,
 - cleaning of workshop floors contaminated with oils, resins and greases,
 - removal of rubber abrasion and paint layers in the painting area,
 - cleaning of equipment and parts in industrial plants,
 - cleaning of tanks, containers, and containers,

- Cold water high-pressure lances with pressures of 1,200 – 2,800 bar:
 - Concrete refurbishment,
 - Cleaning of heat exchangers,
 - Shipbuilding and offshore applications: Cleaning and refurbishment of port facilities (including underwater), cleaning of containers and storage facilities, ship processing in dry dock, in port, or during operation.

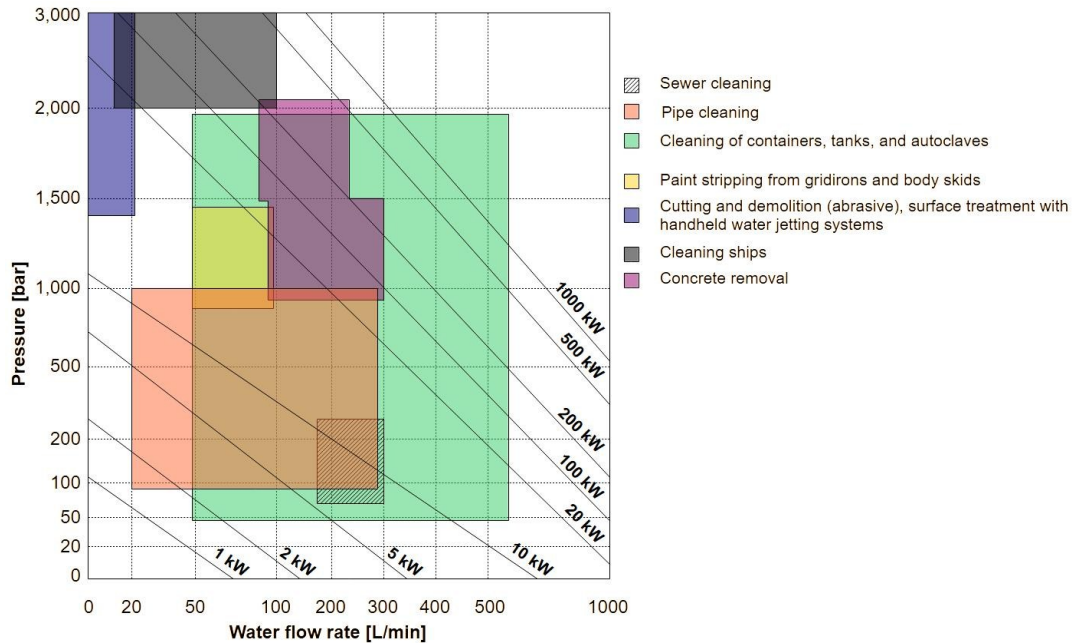


Fig. 1 Areas of application for HD and UHD water jetting (according to 2, 3).

2.1.2 Hazards when working with hand-held high-pressure water jetting systems

Working with HP and UHP water jets involves various hazards. Operating personnel are often not specialists, therefore, significantly higher occupational safety requirements must be met in addition to general water jet safety regulations.

Hand-held water jetting creates wet, slippery working conditions and severely reduces visibility due to atomized spray. Additional hearing protection further impairs situational awareness by limiting the ability to perceive acoustic warning signals or approaching persons. Despite these constraints, operators must maintain full control of the technical equipment. Moreover, hand-held water jet lances are frequently used in tanks, trenches, or other confined spaces characterized by limited clearance and unstable ground, which further restricts operator mobility. In such environments, work often has to be carried out in prone, supine, or overhead positions, increasing the risk of rebound from blasted components.

Under these demanding conditions, numerous potential hazards arise, including [4]:

- Aerosol formation impairing visibility,
- Recoil forces of hand-held spray guns (sudden changes exceeding 15 % of the recoil force are considered hazardous),
- Short term contact between body parts and the UHD water jet, resulting in severe cutting injuries,
- Defective hose lines,
- Release of hazardous substances due to the detachment of product residues (rebound of product material),
- Risk of slipping and falling, as well as loss of balance, etc.,
- Wearing of hearing protection.

Human skin can already be penetrated at relatively low pressures of 40–70 bar. Water jets operating at lower pressure but higher water flow rates – typically 50–60 l/min – are particularly dangerous and may cause more severe human skin than high-pressure jets with lower flow rates. For comparison, a UHP

water jet acting on an area of 0.8 mm² generates an energy density of approximately 300 N/mm², corresponding to a pressure of about 3,000 bar.

2.1.3 Accidents associated with hand-held high-pressure water jets

Reliable statistical data on accidents involving high-pressure water jetting systems are scarce. This is largely because the number of such accidents is comparatively low when contrasted with more common injuries, such as cuts caused by knives or sharp edges, and they are therefore not reported separately in published accident statistics. Case reports from the German Social Accident Insurance Institution for the construction industry (BG Bau), as well as data from the literature, generally do not provide information on the type of protective clothing worn at the time of the accident.

The German Social Accident Insurance (DGUV) has, however, documented consistently high overall occupational accident figures for many years (300 reported accidents per year) resulting in at least three days of incapacity for work. One fifth of these accidents occur in the construction sector, while nearly two thirds take place in industry and trade [1]. Between 2007 and 2014, BG Bau recorded 18 accidents involving high-pressure water jetting equipment operating at pressures between 350 and 2,500 bar and using various nozzle types. These incidents resulted in injuries to a total of 30 body parts, and in all cases the duration of incapacity for work was at least one month.

Typical activities/accident scenarios included exposure of reinforcement (concrete refurbishment), cleaning of paint booths, stripping work, derusting, paint removal, truck cleaning, removal of plaster layers, bridge rehabilitation and façade cleaning [5]. Between 2010 and 2013, other accident insurers reported more than 210 accidents involving high-pressure cleaners operating in the pressure range of 150–250 bar.

Typical injuries caused by direct with water jets, which can be prevented or mitigated by appropriate protective clothing – include the following [5, 6, 7]:

- Shoot through shoes and feet caused by the water jets,
- Injection injuries involving contaminated fluids affecting the lower and upper limbs, torso, hands and forearms, and in some cases resulting in severe injuries to the back.

Such injuries are often slow to heal and may be fatal. For the period from 2004 to 2007, BG Bau reported the following costs associated exclusively with cut injuries resulting from accidents involving high-pressure water jet systems (18 accidents, 30 injured body parts) [5, 8]:

- Foot: €845–2,584
- Head: €1,846
- Arm: €4,402
- Lower leg: €4,683
- Torso/abdomen: €8,708
- Thigh: €47,967–100,112
- Hand: €10,033–82,290.

2.2 Protective clothing for work with hand-held high-pressure water jetting systems

At present, the following protective clothing systems are available on the market:

- TurtleSkin® WaterArmor from Warwick Mills, Inc., New Ipswich/USA [9],
- AQUA SAFE SUIT, CESCO, North Charleston/USA [10],
- protective clothing from TST Sweden AB, Kinna/Sweden [11],
- DEHNcare® WJP from DEHN + SÖHNE GmbH + Co. KG, Neumarkt/Germany [12].

The first three systems provide partial frontal protection against the forces occurring during operation of hand-held water jet lances. Their protection effect is based on ballistic concepts using multi-layered DYNEEMA® or KEVLAR® fabrics. DEHNcare® WJP is specified for work with fan and rotary nozzles at pressures up to ≤ 1,000 bar.

In initial tests with UHP jets commissioned by STFI within a research project [13], the TST protective trousers did not reach the specified target level of 2,000 bars with a round jet nozzle. They withstood a cold-water jet up to about 800 bars but failed during hot-water cutting even at 800 bars, see Figure 2.

Depending on the test conditions, water-jet cuts of approximately 2 mm to 15 mm were observed in ballistic plasticine, accompanied by fiber penetration into the substrate.







TST trouser – 2,100 bar (round jet nozzle, cold water)		TST trouser – 800 bar (round jet nozzle, cold water)	
Front side	Back side	Front side	Back side
			
			
		Ballistic plasticine: Cut of the water jet: 2 mm	Ballistic plasticine: Cut of the water jet: 2 – 15 mm Fiber entry into the plasticine

Fig. 2 TST trouser, tested with a hand-held waterjet lance.

2.3 Patent situation

In the field of protection against mechanical hazards, plate-based structures are currently known primarily from applications in stab and cut protection (knives, sharp objects, cannulas). At the beginning of 2019, a systematic search of international patent databases was conducted to identify patents relating to the design of such plate structures. The search strategy comprised the following keywords and combinations of terms (in German language):

- BI = stich? AND BI = edelstahl AND BI = nadel? AND BI = handschuh?,
- BI = überlappend? AND BI = stich? (zu viele Treffer),
- BI = überlappend? AND BI = stich? AND BI = metall? (zu viele Treffer),
- BI = überlappend? AND BI = stichschutz,
- BI = schuppenförmig? AND BI = stich? AND BI = metall?,
- Plurality of overlapping protective elements, sheet material,
- Stabbing weapon, stabbing attack,
- Against bullets, shotgun pellets, sharp pointed weapon,
- Impact resistant,
- Resistance to penetration.

Patents relating to armour plates and comparable protective structures were identified within the following IPC and CPC classifications:

- ICP: F41H 1/02 (*Armoured or projectile- or missile-resistant garments*),
- ICP: F41H 5/04 (*Armor; armor plates composed of more than one layer*),
- ICP: F41H 5/08 (*Armor; armor plates, for personal use*),
- CPC: F41H 5/0492 (*Layered armour containing hard elements, e.g. plates, spheres, rods, separated from each other, the elements being connected to a further flexible layer or being embedded in a plastics or an elastomer matrix*),
- ICP: A41D 3/00 (*Overgarments (fur garments A41D 5/00; for children A41D 11/00; professional or sporting protective garments A41D 13/00)*),
- ICP: A41D 19/015 (*Protective gloves*).

The identified patents can broadly be classified into two categories: those relating to discrete protective elements and those focusing on protective coatings.

Protective elements

- DE G 94 21 076.4 (expired) [14], EP 0657110 (withdrawn) [15], DE 4341039 (expired) [16]: The utility model describes a glove designed to protect against mechanical injuries from sharp objects, such as syringes (waste sorting). Protection is provided by multiple overlapping, elastically flexible plates made of high-alloy stainless steel (thickness 40 μm) inserted between two layers of tricot fabric. Additionally, the plates are individually sewn into a polyamide fabric cover to reduce friction and prevent sharp edges. The plates can be fixed to the material layers by stitching, riveting, or gluing. The outer of material layer is outside coated to be liquid-proof.
- DE 202008008806 (expired) [17]: The patent describes a protective glove for protecting the hand from mechanical injuries caused by pointed and/or sharp objects. The base material is partially reinforced with overlapping, scale-shaped flat plastic elements, typically made of ABS or polypropylene, which can be sewn, glued, or molded into the base material. An example of such a glove is marketed as “StichStop Plus 180” by KCL GmbH, Eichenzell. The plates are not resistant to water jets in the required pressure range.
- DE 10047977A1 (expired) [18]: This patent describes a penetration-resistant protective layer consisting of a flexible, flat carrier substrate and a plurality of flat plastic elements (epoxy resin, PC, POMH, PMMA, PHA, PPS, and PEEK, optionally filled with silicon carbide or aluminum oxide). The elements are arranged offset but not overlapping, or in a scale-like pattern, and bonding, embedding, or printing. At least 80 % of the total substrate surface is covered by the elements. Intentional gaps between elements may allow penetration by cutting or stitching tools.
- WO 88/06413 (expired) [19]: This patent describes protective material composed of small plates (round, oval, rectangular, or square, 3–15 mm) arranged in offset, overlapping rows on a base material. Plates are sewn or glued and have thicknesses between 0.05 mm and 0.5 mm.
- WO 92/08094 (expired) [20]: This patent describes a body armor (stab protection) with multiple protective elements. The elements are made of an impact-resistant glass composite material and are designed and arranged in such a way that they at least impede the intended contact of a stabbing weapon. At their upper end, the protective elements are mounted on a fabric by means of a small rivet-like fastener. A protective element has a length of 90 mm, a width of 50 mm, and a thickness of 2 mm.
- DE 29807162 (expired) [21]: The invention relates to a flexible stab protection element made of ring-bound, overlapping (light) metal plates, such as aluminum and titanium, but also made of solid-coated plastics or composites or composite structures. The protective element is shaped to fit the contours of the upper body, in line with the cut design of ballistic protection packages or protective plates. It is embedded in a soft, flexible foam or fixed between at least two outer layers using adhesive. The plates overlap to create a surface with no holes or only small hole cross-sections. The metal plates should have a thickness between 0.1 mm and 2 mm.
- DE 69707464 T2 (expired) [22], US 5,906,873: A flexible, bendable, stretchable, and twistable fabric retains its necessary properties thanks to an arrangement of loosely coupled small plates that are loosely interlocked (form-fitting) by tabs. The plates are fixed together by a plurality of rivets. They are made of a hard, strong, nonbrittle material (metal, metal alloy, plastic, and ceramic).

Other patents inserting armor elements are described in DE 202006019711 U1 [23] (also WO 2008080611 A2), WO 2012166624 A1 [24], WO 9321492 A1 [25], US 4,442,150 (A) [26], or US 5,515,541 (A) [27].

Not patented, but from interest, is Martini's study on the development of flexible, bio-inspired armor based on overlapping ceramic scales (28). Ceramic strips pre-structured by laser are glued to pre-stressed elastomer strips, e.g. made of polyurethane. The segments of the ceramic material are then broken and the elastomer strip is relaxed. This causes the ceramic segments to overlap in a scale-like pattern.

Coatings

- DE 102016202546 A2 (in force) [29], (WO 2017140908A1, EP 3416512): The invention describes a composite structure for stab protection for protective textiles. The composite consists of layers of surface elements with a Mohs hardness of 3 to 10, consisting of the group metal (aluminum, titanium, steel, carbide), sheet metal, polymer (aramid, high-strength polyolefin, epoxy resin, polyurethane, silicone, siloxane, rubber and combinations), ceramic materials (silicate ceramics, oxide ceramics, non-oxide ceramics, and combinations), quartz, and combinations thereof, as well as an embedding material. The surface elements of different layers are arranged in a staggered manner. The plate-shaped surface elements are designed in particular as cuboids or prisms. They have a length or width of 0.25 mm to 10 mm, preferably 1 mm to 3 mm, and a thickness of 0.025 mm to 2 mm, preferably 0.1 mm to 0.5 mm.
- US 5,200,263 (expired) [30], US 5,407,612 [31]: A puncture- and cut-resistant composite material consists of at least one elastomeric layer made of polyurethane, latex, nitrile or vinyl rubber, neoprene or similar, which contains a large number of flat, small, thin (< 0.05 mm) and mutually overlapping plates made of carbon steel, stainless steel, hard non-ferrous metals, titanium alloys. The plates are essentially aligned parallel to the plane of the elastomeric layer. Due to their mutual overlap, the plates cover more than 99 % of the surface. The size of the plates is variable and depends on the application (e.g., round plates with a diameter of 1.5–4 mm).

Other patents describe platelet-embedded coatings, e.g., US 5,368,930 and US 5,601,895 (A) [32].

None of these patents mention protection against high-pressure water jets.

Protective clothing

The design of TurtleSkin® WaterArmor protective clothing is described in patent WO002000024276 “Penetration resistant garment” [33] (not valid in Germany). Gaiters are also mentioned here as a protective element. The protective clothing material itself, from which the protective elements are constructed, is protected by patents US5565264 [34] (valid) and US5837623 [35] (valid). It consists of a large number of layers (at least 10) of highly dense woven fabrics in plain weave. The warp and weft thread density is between 27 thread/cm and 39 thread/cm of Kevlar® multifilaments of 222 dtex. The degree of coverage of the warp threads by the weft threads is up to 100 %, preferably 75 %. To increase the penetration resistance and to improve the erosive properties of the water jet, the high-density fabric can be coated or impregnated with a curable material (epoxy resin, cross-linked polyester resins, and polyether resins) that additionally contains fillers of a crystalline material such as ceramic, garnet, metal, silicon carbide, aluminum oxide, or diamond in mesh sizes of at least 150 or finer, see US7393588 [36] (valid), and combined with a nonwoven fabric (0.4–0.6 mm thick) made of synthetic yarns of at least 55 dtex.

Patent US7393588 describes a puncture-resistant composite material with a compressive strength of 300 N/mm² and a total surface mass of 340–850 g/mm², consisting of a flexible fiber layer provided with a solid “inflexible” coating. The rigid coating is applied in a pattern of overlapping segments with a shear strength of at least 3.45 MPa, with gaps between segments measuring 50–400 % of the layer thickness. The binder for the segments is based on a resin system. These composite materials are used for cut protection, ballistic protection, and protection against UHD water jets.

TST protective clothing is not protected by patent law.

2.4 Own research related to the development of protective clothing material for hand-held water jet guns

Within the framework of the results discussion of a research project [13], two DIN A4 specimens – a special knitted polyester fabric and a DYNEEMA® needle-punched nonwoven – were provided to the STFI by a project partner for high-pressure water-jet testing. Surprisingly, a composite consisting of two layers of this special knitted fabric, two layers of the DYNEEMA® needle-punched nonwoven, and four layers of a DYNEEMA® ballistic film withstood ultra-high-pressure (UHD) water jets up to 2,000 bar. This represented the best result achieved to date, including in comparison with the competing TST product, which failed at pressures below 1,000 bar during testing.

Owing to the very small stitch wale and course spacing of the knitted fabric and the use of a suitable, high-density knit, the water jet did not penetrate beyond the second knitted layer. This provided evidence that the knitted protective layer does not necessarily need to be manufactured from high-strength fibers such as UHMW-PE; rather, the required protective performance can be achieved through intelligent material design. With regard to protective performance against high-pressure (HD) and ultra-high-pressure (UHD) water jets, the following results were obtained:

- Fun nozzle with a 30° spray angle (cut with narrow jet side):
 - 1,500 bar: with 2 layers of knitted fabric (1,275 g/m²)
 - 1,050 bar: with 1 layer of knitted fabric (637 g/m²)
- Rotary nozzle with round jet (OrbiMaster):
 - 1,500 bar: with 2 layers of knitted fabric (1,275 g/m²),
 - 1,000 bar: with 1 layer of knitted fabric (637 g/m²).
- Round jet nozzle (sapphire, form 19):
 - 850 bar: with 6 layers of knitted fabric 2 (3,824 g/m²),
 - 550 bar: with 3 layers of knitted fabric 2 (1,912 g/m²).

Figure 3 shows the types of water jet nozzles.



Fig. 3 Types of water jet nozzles (Image was generated using AI.).

These results indicate that, using the knitted fabrics, protective performance against water-jet applications employing round jet nozzles and fun nozzles can be achieved at target pressures of up to 1,500 bar with masses per unit area of the protective layers of approximately 1,280 g/m².

When round jet nozzles are used, the knitted fabrics fail at these pressures because the energy of the water jet is too highly concentrated on the textile surface. Masses per unit area of the protective layer exceeding 3,800 g/m² are required. In addition to the increased weight, the protective textile would become extremely stiff and would no longer provide any wearing comfort. Such assemblies would not be acceptable for workers.

Within the project, the idea of a new concept for the design of protectors was developed, which in initial tests demonstrated protective performance against round jets up to 1,550 bar, see Dietzel (37). Higher pressures could not be tested, as the structures disintegrated during water-jet cutting and were therefore no longer available for further testing. The manufacture of these new protectors will require prior development in terms of materials, design, and processing technology.

3 Method

3.1 Specification of the requirements profile for protectors for work with hand-held ultra-high-pressure water jet lances

The approach to manufacturing the protectors has been to develop of scale-like metal platelet structures that provide 100 % coverage of a tightly knitted backing fabric, even when the scales shift slightly due to the movement of the worker and/or the effect of high-energy water jets. The metal platelet selection includes:

- the size and shape of the scales
- the thickness of the metal platelets (stainless steel, aluminium if required) which affects the mass per unit area and the level of protection
- the arrangement of the platelets (degree of coverage).

In order to estimate the amount of work (number of platelets) and the mass of the protectors, the required number of platelets and the masses for a 0.3 mm or 0.5 mm thick stainless steel were first calculated for different platelet shapes (rectangle, circle, oval) and platelet sizes, see Table 1. Figure 4 shows the designs of the scale-like protector structures.

Table 1. Protector mass depends on the shape and size of the platelet and on the thickness of the stainless steel sheets.

Platelet shape	Platelet size							
	250 mm x 250 mm				400 mm x 400 mm			
	Length [mm]	Wide [mm]	Number of platelets [pc.]	Mass steel (0.3 mm) [kg]	Mass steel (0.5 mm) [kg]	Number of platelets [pc.]	Mass steel (0.3 mm) [kg]	Mass steel (0.5 mm) [kg]
Rectangular shape	15	10	962	0,342	0,570	2,462	0,875	1,458
	20	15	463	0,329	0,549	1,185	0,843	1,404
Round shape	15	15	641	0,268	0,447	1,231	0,515	0,859
	20	20	347	0,259	0,431	667	0,496	0,827
Oval shape	15	10	962	0,268	0,447	1,846	0,515	0,859
	20	15	463	0,259	0,431	889	0,496	0,827

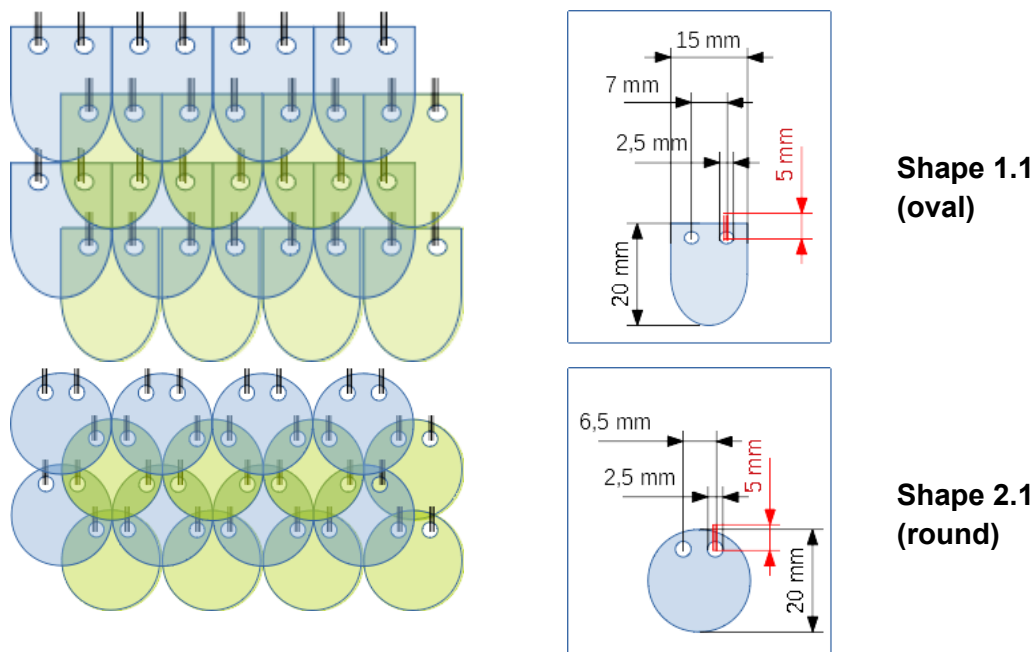


Fig. 4 Design of the scale-like protector structures.

3.2 Selection of metal sheets and the knitted backing fabric

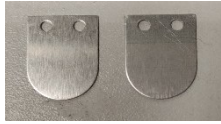
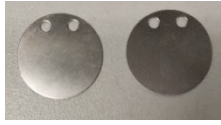
3.2.1 Selection of metal sheets

Stainless steel and aluminium sheets with varying strength and ductility, in thicknesses of 0.3 mm or 0.5 mm, were procured to make the platelets. The platelets were produced by punching. During the punching process, some of the platelets were deformed and burr formation was observed. Table 2 summarizes the final selected platelets. The presence of burrs and slight deformation increased the

handling difficulty and complicated removal from the magazine of the button-sewing machine. Alternative methods for cutting the platelets include:

- Laser cutting: Burr formation may occur due to molten metal. Platelets can also be thermally deformed due to heat input.
- Chemical etching process: An UV-sensitive film can be applied to the cleaned metal sheet. The film is then digitally exposed to light (“printing of the platelets”). Unexposed areas are removed, and the metal is etched in the exposed regions. This method produces burr-free, stress-free parts without applying mechanical force or heat, preserving the material properties. Furthermore, it allows for almost unlimited geometric complexity for nearly any metal.

Table 2. Aluminium alloy and stainless steel alloy for the platelets.

Metal alloy	Thickness	Platelet shape	Picture
Aluminium Al Mg Si1 / EN AW-6082	0.5 mm	Shape 1.1	
Stainless steel 1.4310	0,3 mm	Shape 2.1	

3.2.2 Selection of the knitted backing fabric as substrate for the protectors

A high-density knitted fabric made of textured polyester yarns (DIOLLEN[®], dtex 334/72x1; TWD Fibres Service GmbH, Deggendorf/Germany) was selected as the substrate for the scale-like protector structures (37). This fabric has previously demonstrated an effective protection against both rotary nozzles and fun nozzles at pressures up to 1,500 bar. The protector structures are subsequently covered with a waterproof, highly abrasion resistant f CORDURA[®] fabric.

The knitted fabric was produced on a RH 216-I (E24) tubular circular knitting machine from Terrot GmbH, Chemnitz, in an interlock pattern (RRG: right/right/cross). A cross section of the knitted fabric is shown in Picture 5.

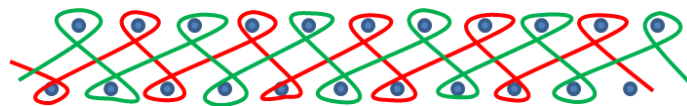


Fig. 5 Yarn paths (cross section) of the knitted backing fabric in interlock pattern.

The machine settings were as follows:

- Cylinder diameter: 18'',
- Gauge: E24,
- Number of feeders: 30,
- Number of needles: 1,356,
- 2+2 needle tracks in dial and cylinder,
- Positive feeding,
- Stich cam: 2.3,
- Take-down value: 100 %,
- Production speed: 33 rpm.

To improve the dimensional stability of the knitted fabric and to prevent the curling edges of the samples, the knitted fabric was heat-set at 190 °C (Mathis Coating and Finishing System BA 6792, WERNER MATHIS AG, Oberhasli/Switzerland).

3.3 Application of platelets on textile substrate

In addition to technical embroidery, automatic button sewing machines are suitable for applying paillette-like elements. Thus, the electronic high-speed button-sewing machine Bruce BRC-T1900G manufactured by JACK TECHNOLOGY CO., LTD. (China) was used for fixing the metal platelets to the substrate. Compared to other button-sewing machines, this system allows sewing of platelets with larger hole spacing (> 5 mm). A double-lockstitch was used. The machine was modified by Pfeil GmbH, Mühlau. Pfeil GmbH with a modular, integrable system including control technology for the automated feeding of metal platelets to a holder/clamp, as shown in Figure 6.



1. Leg button
2. Magazine
3. Transfer arm with suction head
4. Sewing station with laser positioning and hook
5. Foot pedal
6. Touch screen
7. Bobbin

Fig. 6 Electronic high-speed button-sewing machine Bruce BRC-T1900G.

To fix the platelets onto the textile substrate, a novel concept for storage and transport of the platelets to the sewing station was developed (Figure 7). The internal geometries of the magazines were designed to match the shapes of the individual platelets, ensuring precise pre-positioning.

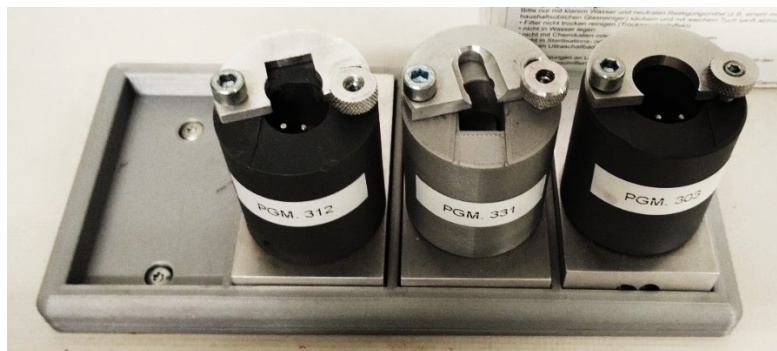


Fig. 7 Magazines for pre-positioning the metal platelets.

3.4 Fixation of metal platelets on the knitted substrate

During the project progression, it was observed that the platelet structures can spread apart, particularly in areas corresponding to joints, when the garment is in motion. The displacement of the metal platelets causes them to separate or flip open, thereby weakening the protective effect of the structure in these regions. This creates the risk that high-pressure water jets may penetrate beneath the platelets, rendering the protective system ineffective and potentially causing serious injury to the worker.

To address this problem, selected samples were coated with a flexible film applied over the metal platelet structures. Technically, this can be achieved either by knife application of a thin, flexible, solvent-free film or by applying a thermoplastic coating using a hot-melt process (wide-slot nozzle).

For direct coating, as shown in Figure 8, the low-viscosity, solvent-free, two-component liquid silicone rubber ELASTOSIL® LR 6250 F TRANSPARENT was used. ELASTOSIL® LR 6250 F was applied to the platelet samples using the hand-coating device from Werner Mathis AG, Oberhasli, Switzerland. The following parameters were used: 100 parts ELASTOSIL® LR 6250 F TRANSPARENT + 2 parts crosslinker W; air squeegee; blade gap of -1,5 mm; airflow of 900 rpm; drying temperature of 150 °C; drying time of 3 minutes.



Fig. 8 Knife coating of the metal platelets.

3.5 Testing and evaluation of the textile-physical properties and of the protective effects against high-pressure and ultra-high-pressure water jets

3.5.1 Textile-physical properties

The physical-textile properties were characterized according to the following standards:

- Stitch density: DIN EN 14971:2006-04
- Thickness: DIN EN ISO 5084:1996-10
- Mass per unit area: DIN EN 12127:1997-12
- Air permeability: DIN EN ISO 9237:1995-12
- Bending stiffness: STFI-PV PT 17:2012-04
- Stress-strain behaviour: DIN EN ISO 13934-1:2013-08
- Tear resistance: DIN EN 388:2017-01
- Abrasion resistance: DIN EN 388:2017-01.

3.5.2 Evaluation of the protective effect of the protector structures against high-pressure and ultra-high-pressure water jets

As no standardized testing and certification procedures for protective clothing against high-pressure water jets existed, the GS-IFA-PI5 test specification was developed in 2017 by the Protective Clothing Subcommittee of the German Social Accident Insurance (DGUV) in cooperation with the Institute for Occupational Safety and Health of the DGUV (IFA) (38, 39, 40). This specification formed the basis for the new DIN 19430 standard, "Protective clothing – Clothing against high-pressure water jets – Requirements and test methods." Table 2 provides an overview of relevant test parameters.

Hammelmann GmbH, Oelde, a co-initiator of the standard, provided a test robot capable of varying all relevant parameters including water pressure, water flow rate, nozzle geometry, distance between nozzle and textile sample, and exposure time of the water jet. Figure 9 shows the test robot.

Table 2. Performance levels and test parameters for protective clothing against high-pressure water jets up to 150 N reaction force (test parameters related to 165 N, safety factor is included).

Nozzle	Fun nozzle			Rotary nozzle				Round jet nozzle			
Performance level	$F_{150}200$	$F_{150}500$	$F_{150}1000$	$R_{150}200$...	$R_{150}2000$	$R_{150}3000$	$P_{150}200$	$P_{150}500$...	$P_{150}2500$
Pressure [bar]	200	500	1000	200	...	2000	3000	200	500	...	2500
Volume flow rate [l/min]	52,5	32,0	23,6	53,7	...	17,9	13,0	51,0	31,5	...	15,3
Nozzle diameter [mm]	2,9	1,8	1,3	2x2	...	0,65x2	0,5x2	2,4	1,5	...	0,7
Jet distance [mm]	$75 \pm 3,75$										
Traverse speed [m/s]	$0,5 \pm 0,025$										

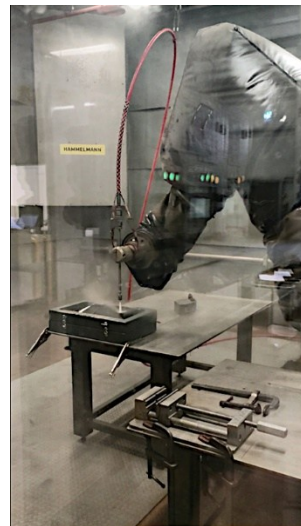


Fig.9 Test robot for determining the resistance of the protector material to ultra-high-pressure water jets according to DIN 19430 (Hammelmann GmbH, Oelde).

4 Results

4.1 Textile-physical properties of the knitted backing fabric

The stitch density, the thickness, the mass per unit area, and the air permeability of the knitted backing fabric are summarized in Table 3. Maximum tensile force and elongation at break as well as the bending force of the knitted fabric are given in Table 4.

Table 3. Stitch density, thickness, mass per unit area, and air permeability of the knitted fabric.

Stitch density		Thickness	Mass per unit area	Air permeability
Stich wales	Stich courses			
[1/cm]	[1/cm]	[mm]	[g/m ²]	[l/m ² /s ²]
12,27	22,80	1,14	637,38	204,20

Table 4. Maximum tensile force, elongation at break, and the bending force of the knitted fabric.

Direction	Maximum tensile force [N]	Elongation at break [%]	Bending force [mN]
Lengthwise	2,219.98	217.12	99.68
Crosswise	1,314.13	101.90	37.60

The knitted fabric was also tested according to the standard DIN EN 388:2017-01 for testing gloves offering protection against mechanical risks. The performance levels are given in Table 5. The test results are shown in Table 6. Minimum requirements for the polyester knitted fabric were set as tear strength level 4 (≥ 224.5 N) and puncture resistance level 3 (≥ 136.0 N). Test results are summarized in Tables 5 and 6.

Table 5. Performance levels for gloves offering protection against mechanical risks according to DIN EN 388:2017-01

Performance level	1	2	3	4	5
Abrasion resistance (number of turns needed until a hole appears on the material)	100	500	2,000	8,000	–
Cut resistance (index)	1.2	2.5	5.0	10.0	20.0
Tearing strength (N)	10	25	50	75	–
Puncture resistance (N)	20	60	100	150	–

Table 6. Knitted fabric properties according to DIN EN 388:2017-01

Abrasion resistance			Cut resistance		Tearing strength		Puncture resistance	
Number of turns	Performance level	Index	Performance level	[N] lengthwise	Performance level	[N]	Performance level	
100–280	1	3,1–3,1	2	224,5	4	136,0	3	

4.2 Protective effect of the protector structures against high-pressure and ultra-high-pressure water jets

The effectiveness of the platelet-based protective structures depends on the overall layer configuration, the metal alloy used, the platelet geometry, and the parameters of the waterjet applications.

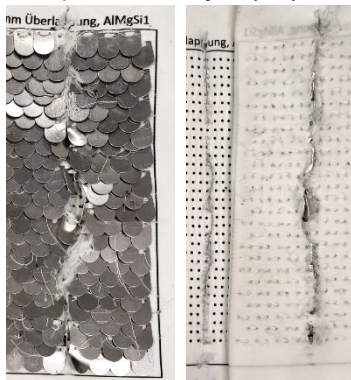
The protective structures were tested both with and without additional layers of knitted fabric described in Section 3.2.2, as well as with and without a waterproof CORDURA® outer cover. The investigated layer configurations comprised platelet structures combined with zero, one, or two knitted fabric layers and, optionally, a CORDURA® cover layer. The specific samples tested at Hammelmann GmbH were selected on site, depending on the intermediate test results. Selected samples are listed in Table 7. Further results can be found in the report of Dietzel (37).

Protective performance was consistently lower for round-shaped platelets than for oval-shaped platelets. Representative test results are presented in Figure 10. Owing to the high cost of a single test day, each test condition was evaluated only once. The assessment focused on damage on the body-facing side of the layer system, as well as on platelet deformation and displacement. A sample was classified as having passed the test if no cuts were detected in the bottom layer.

Table 7. Knitted fabric properties according to DIN EN 388:2017-01

Test	Metal	Platelet geometry	Pressure [bar]	Silicone coating	Additional knitted fabric	CORDURA® cover
V1	Al Mg Si1 / EN AW-6082	Oval-shaped	2,000	/	X	/
V8	Al Mg Si1 / EN AW-6082	Oval-shaped	2,000	X	X	X
V17	Al Mg Si1 / EN AW-6082	Oval-shaped	500	/	X	X
V18	Al Mg Si1 / EN AW-6082	Oval-shaped	500	/	X	X
V19	1.4310	Round-shaped	500	/	X	X
V23	Al Mg Si1 / EN AW-6082	Oval-shaped	1,000	/	/	X
V24	1.4310	Round-shaped	1,000	/	X	X
V26	Al Mg Si1 / EN AW-6082	Oval-shaped	1,000	/	X	X
V27	1.4310	Round-shaped	1,000	/	X	X
V28	Al Mg Si1 / EN AW-6082	Oval-shaped	2,000	/	X	X

Oval-shaped aluminium platelets, round jet nozzle, 2,000 bars, second knitted fabric as an additional protective layer (V1)



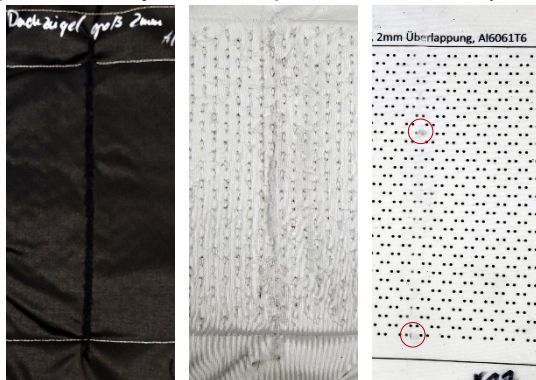
⇒ Cut of the second knitted fabric

Oval-shaped aluminium platelets, round jet nozzle, 2,000 bars, second knitted fabric as an additional protective layer + waterproof black cover (V8)



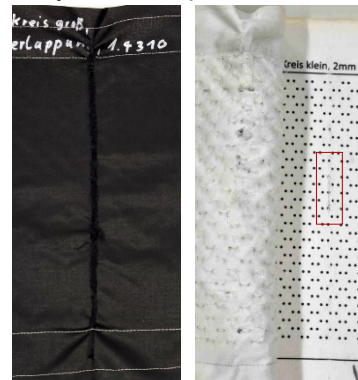
⇒ Cut of the second knitted fabric

Oval-shaped aluminium platelets, round jet nozzle, 500 bars, second knitted fabric as an additional protective layer + waterproof black cover (V17)



⇒ Platelets only bent
⇒ No cut of the second knitted fabric, only small scratched areas

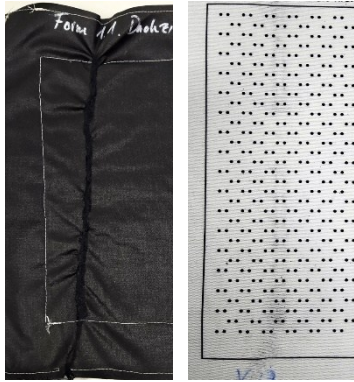
Round-shaped stainless steel platelets, round jet nozzle, 500 bars, second knitted fabric as an additional protective layer + waterproof black cover (V19)



⇒ Seam of 2 platelets is cut. Platelets are pushed sideways and partially fall out of the structure.
⇒ Small cut in the second knitted fabric

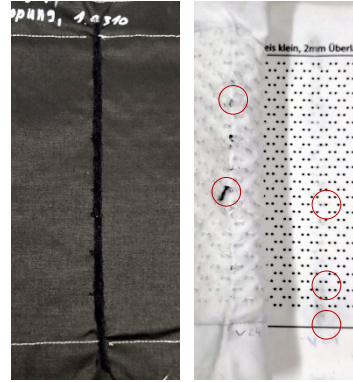
Oval-shaped aluminium platelets, fun nozzle, 1,000 bars, waterproof black cover (V23)

Round-shaped stainless steel platelets, fun nozzle, 1,000 bars, second knitted fabric as an additional protective layer + waterproof black cover (V24)



⇒ No cut of the second knitted fabric

Oval-shaped aluminium platelets, rotary nozzle, 1,000 bars, second knitted fabric as additional protective layer + waterproof black cover (V26)



⇒ Partial cut in the knitted fabric of the platelet structure

Round-shaped stainless steel platelets, rotary nozzle, 1,000 bars, second knitted fabric as additional protective layer + waterproof black cover (V27)



⇒ No cut of the second knitted fabric

Oval-shaped aluminium platelets, rotary nozzle, 2,000 bars, second knitted fabric as additional protective layer waterproof black cover (V28)



⇒ No cut of the second knitted fabric



- ⇒ Platelets disordered
- ⇒ Large area of the second knitted fabric as additional protective layer damaged

Fig. 10 Examples of the tests with ultra-high-pressure water jets according to DIN 19430.

When water jets, especially a round jet nozzle, impinge directly on the seams fixing the platelets, the seam is cut, and platelets are displaced or partially ejected, see Figure 11. The result is an almost straight cut. To prevent this, vertical seams were applied.

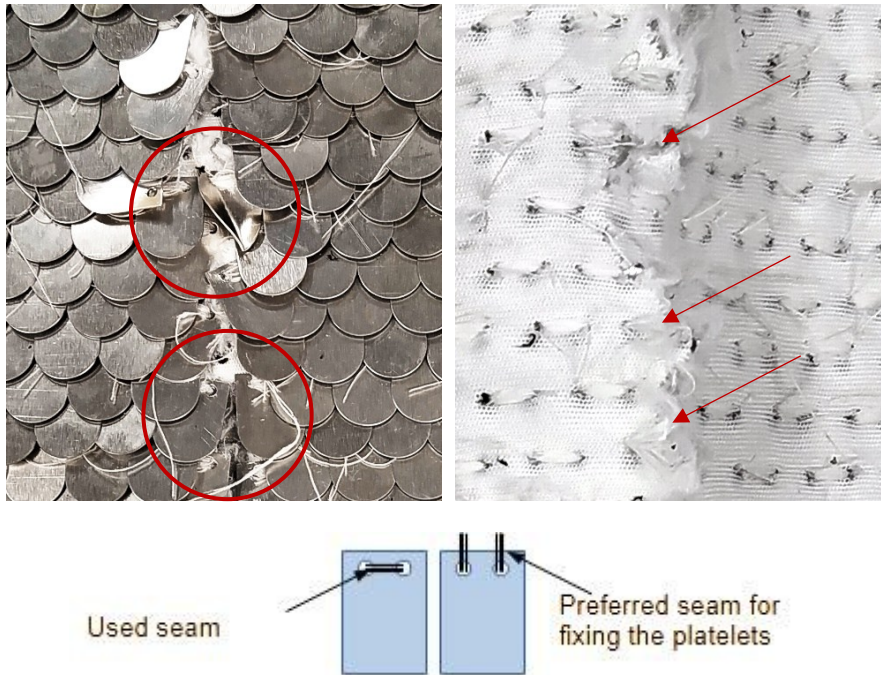


Fig. 11 Missing platelets due to cut the seam.

Sharp corners of oval platelets caused puncturing of the knitted fabric (Figure 12); rounding the corners mitigates this effect.



Fig. 12 Sharp corners of the platelets pierce and cut through the knitted fabric.

Applying a thin, flexible polymer coating (PVC or silicone) improves platelet retention (Figure 13).



Fig. 13 Platelets are better fixed in place by a thin coating.

From the results obtained, it can be concluded that:

- The oval-shaped platelet structures provide protection against high-pressure water jets for pressures:
 - Round jet nozzle up to 500 bar,
 - Rotary nozzle up to 1,000 bar,
 - Fun nozzle up to 1,000 bar,
- Increasing platelet size enhances coverage and prevents displacement-induced structural failure, but reduces flexibility and lowers the number of required platelets, reducing production costs.
- A fully automated process for platelet application is recommended.

Further optimization, including larger platelets (~20 × 27 mm) and longitudinal seam placement, could extend protection against round jet nozzles up to 1,550 bar. Future development should also focus on automated handling of the knitted substrate to save resources.

5 Conclusions

A new protective clothing material has been developed for use with handheld ultra-high-pressure water jet guns. The Scale-like protector provides protection against the various water jet applications up to 1,000 bar for flat jet and rotary nozzles and up to 500 bar for round jet nozzles. Protectors can be offered as knee and shin protectors, gaiters or aprons. Protection against water jets of up to 3,000 bar is not currently possible with textile solutions.

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References

1. <https://www.bausicherheit-online.de/d/dehn-soehne-effektiver-schutz-bei-der-arbeit-mit-hochdruckwasserstrahlern/> (Aufruf: 02.09.2019)
2. <http://www.woma-applications.com/deutsch.htm?/cont/de/02.htm> (17.10.2012)
3. <http://www.woma-applications.com/anwendungen.htm> (17.10.2012)
4. Hrsg. Berufsgenossenschaft für Fahrzeughaltungen: BGI 5063-1 „Industriereinigung Schutzmaßnahmen und arbeitsmedizinische Vorsorge“. 1. Auflage, 200
5. Claudia Waldinger: Schutzbekleidung bei Tätigkeiten mit Hochdruckwasserstrahlgeräten - 1. Unfallgeschehen. Informationsveranstaltung der BG Bau, Bereich PSA, München, 10.12.2014
6. Erste Hilfe Hinweise für Ärzte;
http://www.hammelman.de/wAssets/docs/sicherheit/Informationen_fuer_den_Arzt.pdf (27.11.2015)
7. Petzschmann, E.; Jung, D.; Watermann, D.: Einsatz von Flüssigkeitsstrahlern auf Baustellen im Bauhaupt- und Baunebengewerbe. Tiefbau 7 (2002), S. 376–381
8. Claudia Waldinger: Schutzkleidung für Hochdruckstrahl-Arbeiten. In : BauPortal 2 (2018) 130, S. 46–48
9. <https://www.turtleskin.com/collections/waterarmor> (17.12.2025)
10. <https://aquasafesuits.com/water-blasting-equipment-safety-products/> (17.12.2025)
<https://aquasafesuits.com/wp-content/uploads/2025/07/AquaSafeSuit-Catalog-.pdf>
11. https://tst-sweden.com/catalogs/protection_for_waterjetting_and_high_pressure_cleaning/ (17.12.2025)
12. <https://www.dehn.de/de/schutzanzug-wjp-faq> (17.12.2025)

13. Yvette Dietzel: *Entwicklung eines textilen Schutzkleidungsmaterials gegen die Risiken beim Arbeiten mit handgeführten Hochdruck- und Ultrahochdruck-Wasserstrahlern* / Sächsisches Textilforschungsinstitut e.V. (STFI). Chemnitz, 2012. – research report. Bundesministerium für Wirtschaft und Technologie (BMWi), Reg.-Nr. MF 090129
14. Kächele-Cama Latex GmbH, „Schutzbekleidung“, DE G 94 21 076.4, 01.06.1995 (erloschen)
15. Gisbert Scheipers, Andreas Seyler, Günter Müller (Kächele-Cama Latex GmbH), „Schutzbekleidung“, EP 0 657 110 A1, 11.08.1994 (lapsed)
16. Wolf-Dietrich Kniep, Gisbert Scheipers, Andreas Seyler, Günter Müller (Kächele-Cama Latex GmbH), „Schutzbekleidung“, DE 4341039 A1, 08.06.1995 (lapsed)
17. RS Kunststoff GmbH, „Schutzbekleidung“, DE 20 2008 008 806 U1, 23.10.2008 (erloschen)
18. Peter Fackelmann, Carla Alexandra Silva, Anabela Silva (Centro Tecnológico das Indústrias Textil do Vestuário de Portugal), „Durchdringungsfeste Schutzschicht und Verfahren zu deren Herstellung“, DE 100 47 977 A1, 04.04.2002 (lapsed)
19. Krister Kaellstroem (Fristads AB), „A protective device“, WO 88/06413, 07.09.1988 (lapsed)
20. David John Leech, Noel Ayliffe-Jones (Eurocourt Limited), „Durchdringungsfeste Schutzschicht und Verfahren zu deren Herstellung Improvements in or relating to body protecting clothing“, WO 92/08094, 14.05.1992 (lapsed)
21. Marion Koch, „Flexibles Stichschutzelement“, DE 29807162 U1, 17.09.1998 (lapsed)
22. Kim Hwa (Higher Dimension Medical, Inc.), „Stech-, stanz- oder Schnittfester Stoff“, DE 69707464 T2, 29.05.2002 (lapsed)
23. Lothar Müller, „Körperschutzpanzerung, bestehend aus einer Vielzahl von Panzerplatten“, DE202006019711 U1, 30.04.2008 (erloschen)
24. Kim Young-Hwa (Higher Dimension Medical, Inc.), „Fabric assembly including leather substrate“, WO 2012166624 A1, 06.12.2012
25. Kim Patchett, „Armour tiles and flexible armour composed of such tiles“, WO 9321492 A1, 28.10.1993
26. Wolfgang A. H. Greiner, Magnus Mauch, „Flexible two-dimensional material“, US 4,442,150 (A), 10.04.1984 (lapsed)
27. Michael Sacks, „Flexible armor“, US 5,515,541 (A), 14.05.1996 (lapsed)
28. Roberto Martini. Francois Barthelat: Stretch-and-release fabrication, testing and optimization of a flexible ceramic armor inspired from fish scales. In : *Bioinspiration Biomimetics*, 11 (2016) 066001, S. 1–10
29. Dr. Andreas Scherrieble, Dr. Thomas Stegmaier, Hannes Junger, (Deutsche Institute für Textil- und Faserforschung Denkendorf; W + R GmbH), „Verbundstruktur für den Stichschutz, Verfahren zur Herstellung einer Verbundstruktur, Stichschutzeinlage sowie Schutztextil“, DE 10 2016 202 546 A1, 24.08.2017
30. Arnold S. Gould, Larry D. Nichols, „Puncture and cut resistant material and article“, US 5,200,263, 06.04.1993
31. Arnold S. Gould, Larry D. Nichols, „Method for making puncture and cut resistant material and article“, US 5,407,612, 18.04.1995
32. Frank Cunningham, „Flexible puncture proof material“, US 5,601,895 (A), 11.02.1997
33. WO0024276: Penetration resist garment; Warwick Mills, Inc., New Ipswich, USA
34. US5565264: Protective fabric having high penetration resistance; Warwick Mills, Inc. (USA)
35. US5837623: Protective fabric having high penetration resistance; Warwick Mills, Inc. (USA), Charles A. Howland (USA)
36. US7393588: Flexible penetration resistant composite material structure with critical gap geometry in a solid layer; Warwick Mills, Inc. (USA)
37. Yvette Dietzel: *Entwicklung von Protektoren gegen Risiken beim Arbeiten mit handgeführten Hochdruck- und Ultrahochdruck-Wasserstrahlern* / Sächsisches Textilforschungsinstitut e.V. (STFI). Chemnitz, 2023. – research report. Bundesministerium für Wirtschaft und Klimaschutz (BMWK), Reg.-Nr. 49MF190118
38. Walther, C.; Kirchhoff, Chr.; Lüttgens, H.; Mewes, O.; Ziehmer, R.; Dietzel, Y. Clothing for protection against high pressure water jets – new DIN 19430 standard. KAN Brief 3/2021, p 21. ISSN print 2702-4024, ISSN online 2702-4032.
<https://www.kan.de/en/publications/kanbrief/3/21/clothing-for-protection-against-high-pressure-water-jets-new-din-19430-standard>
39. DIN 19430:2021-05. Schutzkleidung – Kleidung zum Schutz gegen Hochdruckwasserstrahl – Anforderungen und Prüfverfahren
40. Walther, C.; Kirchhoff, Chr.; Lüttgens, H.; Mewes, O.; Ziehmer, R.; Dietzel, Y. Clothing for protection against high pressure water jets – new DIN 19430 standard. tema – BVT-Magazin für Beruf und Studium, Ausgabe 01.2022, p 13, ISSN 0722-2874