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ORIGINAL ARTICLE

Pressure-sensitive fasteners for active disassembly

Jef R. Peeters[1] · Wannes Van den Bossche[1] · Tom Devoldere[2] · Paul Vanegas[1] · Wim Dewulf[1] · Joost R. Duflou[1]

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Abstract This paper presents a number of novel active fasteners developed to significantly lower disassembly costs during reconditioning, remanufacturing, and recycling of products. In the initial stage of the fastener development process, the applicability of distinct trigger signals for active disassembly (AD) is evaluated. Based on this evaluation, the high robustness of using a pressure increase or decrease as a nondestructive trigger for AD is demonstrated. Since previously proposed pressure-sensitive fasteners face considerable drawbacks upon implementation in electronic products due to the ongoing trend of miniaturization, a second generation of pressure-based active fasteners is developed. Evaluation of these fasteners by means of axiomatic design techniques and prototyping demonstrates that the presented snap-fits, which make use of a closed-cell elastomer foam, are most robust. Subsequently, the contraction forces that closed-celled foams can exert as a function of an increase in ambient air pressure are experimentally determined. Furthermore, the implementation of pressure-sensitive foam-based snap-fits in both a modem and a payment terminal is described. Results of these experiments demonstrate that the contraction force of a cross-linked metallocene polyethylene closed-cell foams can reach up to 6 N/cm^2 at an overpressure of 2 bar and that the foam-based snap-fits can be released at a pressure increase of 2 bar.

✉ Jef R. Peeters
jef.peeters@cib.kuleuven.be

[1] Mechanical Engineering Department, KU Leuven, Celestijnenlaan 300A, Box 2422, 3001 Leuven, Belgium

[2] TP Vision, Technologiepark-Zwijnaarde 19, 9052 Ghent, Belgium

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1 Introduction

In response to increasing resource prices and consumer awareness, original equipment manufacturers (OEMs) are putting efforts in reducing resource consumption and lowering the environmental load of their products by applying Eco-design [1]. Recent evolutions in European legislation, such as the Waste Electrical and Electronic Equipment (WEEE), End-of-Life Vehicle (ELV), and Eco-design directives, encourage this evolution by extending the producer responsibility. OEMs increasingly extend their responsibility by adopting product-service system (PSS) business models in which customers pay for the delivered service or availability of the service, while the products needed to deliver the service remain property of the OEMs [2, 3].

For products sold in a PSS, high product availability is often requested by the consumer. Therefore, products which fail are, in most cases, directly replaced by a functioning product and the failed products are systematically reconditioned or remanufactured. The most crucial steps of reconditioning and remanufacturing processes, in which products are returned to either satisfactory or original performance, are inspection, cleaning, and reprocessing [4]. Since these operations require access to product components, a reduction in product disassembly costs significantly reduces the costs of reconditioning and remanufacturing operations. Moreover, a reduction in disassembly costs can make product remanufacturing or component reuse the preferred end-of-life (EoL) strategy over a recycling or disposal strategy [5, 6].

In addition, prior research has demonstrated that in a disassembly-based EoL treatment, up to 70 % more precious metals (PMs) can be recycled from electronic products compared to an EoL treatment in which products are directly processed in a shredder [7]. Tests performed in cooperation with OEMs and recyclers have also demonstrated that plastics containing flame retardants (FR), which are increasingly applied in electronic products, can nowadays only be closed loop recycled by applying a disassembly-based EoL treatment [8]. Since electronic products contain a high concentration of PMs and FR plastics, a reduction in disassembly costs has the potential to shift the EoL treatment for these products from a cost factor to a profit-generating activity or to simply reduce treatment costs, as well as lowering the ecological impact generated during EoL treatment [9–11].

Since the efficiency of disassembly operations can be significantly influenced by an optimization of the product structure, many efforts have been made in prior research focusing on design for disassembly (DFD) [12]. An example of DFD is the modularization or grouping of components, which reduces the number of disassembly steps and, in this manner, facilitates the disassembly process [13]. Whereas DFD rules also strongly overlap with design for assembly guidelines and can result in significant reductions in overall manufacturing costs [12], the adaptation of DFD still requires human intervention for the disassembly process.

To lower the human interaction during the disassembly process and the related costs, prior research focused on semi or full automation of standard disassembly operations for, among others, washing machines [14], personal computers [15], LCD monitors [16], mobile phones [17, 18], and remote controls [19]. However, to date, only a limited number of cases have been documented in which automated disassembly has been implemented in a robust and industrially viable fashion, such as the remanufacturing of single-use cameras [20]. Further industrial adoption of such automated disassembly cells is limited due to the high diversity of applied fasteners, as well as the broad variety of products and the variation in the condition of returning products [16, 19, 21]. Due to this diversity, advanced product recognition and intelligent, versatile handling techniques need to be called upon, resulting in nonrobust and costly procedures. Additional problems that have been identified for fully automated disassembly are the gripping of very irregular shapes, the need to simultaneously perform multiple actions, such as component removal and cable cutting, and the extraction of obstructed components [22].

Furthermore, the economic viability of disassembly operations and the optimal depth of disassembly can also be significantly influenced by the selected joining methods [23]. In order to address these shortcomings of conventional disassembly, the presented research focuses on active disassembly (AD), which requires the implementation of active fasteners for which a specific external trigger or a combination of triggers can initiate a simultaneous unfastening process of multiple connections without the need for direct, individual, physical contact between a disassembly tool and the product or the need to position a disassembly tool relative to the product [20]. Since, in an AD process, all active fasteners can be simultaneously released within multiple products, one of the main advantages of AD is that it enables to drastically reduce disassembly costs. Moreover, AD does not require product-specific disassembly setups, and depending on the required trigger to initiate the AD process, human interaction can be made redundant.

This article reports on the development, evaluation, and implementation of innovative pressure-sensitive fasteners for AD, which can be simultaneously released by changing the surrounding air pressure. In the initial phase of the fastener development process, the applicability of several triggers for AD was evaluated by means of multiple experiments of which the results are presented and compared with the outcome of prior research in the second section. In the third section, the results of the experiments performed to optimize the embodiment of the developed fasteners and to evaluate the robustness of the developed fasteners are discussed.

2 Trigger selection for AD

For numerous electronic products, the cost of reverse logistics and repair is lower than the total production costs of electronic products. As a result, most OEMs consider repairability a requirement from an economic perspective to efficiently deal with product failures during the product warranty period or to deal with products which fail while used in a PSS. Therefore, only the applicability of trigger signals for the initiation of a nondestructive AD process is explored in this article, excluding partially destructive triggers that have also been explored in prior research [20, 24].

Prior research has indicated that pressure and temperature offer the highest trigger potential for nondestructive AD, since these triggers do not restrict the freedom of the designer or the functionality of the product [25]. However, in this research, the use of electromagnetic waves in combination with the principle of resonant inductive coupling [26] was not explored. Therefore, the applicability of the triggers pressure, temperature, and electromagnetic waves has been investigated further by means of practical experiments and discussions with different product specification and technical domain specialists. Table 1 compares the extreme conditions to which a product could be exposed during its life cycle with the destructiveness for electronic products of the triggers, which were identified to have the largest potential for nondestructive AD. Furthermore, an indication is provided whether the required energy for applying the triggers is high or low based on

Table 1 Triggers with the highest potential for AD for electronic products

Trigger	Amount of energy required (indication of theoretic energy/TV set)		Max. OEM's test boundary	Extreme conditions during use phase	Max. boundary without damage to product	Potential AD trigger range
Increase pressure	Low	(20 kJ)	Not tested	1.2 bar	<7 bar	2–7 bar
Decrease pressure	Low	(12 kJ)	Not tested	0.5 bar	>0.1 bar	0.1–0.4 bar
Increase temperature	High	(1.3 MJ)	70 °C	90 °C	110 °C	95–105 °C
Electromagnetic waves (RF)	Low	Intensity dependent	3 V/m @ 80–1000 MHz and 30 V/m @ 1800, 2600, 3500, 5000 MHz		Frequency dependent	Frequency dependent

the theoretically required minimal energy to apply the trigger within the potential AD trigger range. This comparison allows indicating the trigger range that can be used for AD for the purpose of repair, remanufacturing, or reconditioning, while avoiding unwanted disassembly during the distribution and the use phase.

2.1 Temperature

Significant part of the research on AD yet is based on shape memory materials, which are able to return to an initial shape when heated above the trigger temperature [27–32]. One case of industrial implementation, albeit discontinued, concerns shape memory alloy (SMA) fasteners in a Sharp mobile phone charger, named "Easy Release Technology" [7, 8]. Besides the lack of a business model to recover the EoL mobile phone chargers, other factors that were cited as reasons for the discontinuation of the implementation of these SMA fasteners include the high production cost of the fasteners and the low efficiency of the heating process [9]. Besides SMAs, also shape memory polymers (SMPs) have been developed, which can be produced at a significantly lower cost. However, due to the lower trigger temperature of SMPs and because SMPs can return to their initial shape when subject to a kinetic shock, SMP fasteners are characterized by a low robustness [33].

Next to shape memory materials, temperature-sensitive tapes have been developed that contain thermoplastic expandable microspheres. Similar microspheres are commonly applied as blowing agents for the production of polymeric foams and consist of a small amount of hydrocarbon, a volatile agent, a sublimation agent, water, or an explosive agent, encapsulated by a gas-proof polymeric shell. When exposed to heat, the shell softens and the content gasifies, causing the microspheres to expand [34, 35]. Because the expansion of the microsphere destroys the bonding, such tapes can be suddenly and completely released when heated above the phase change temperature of the encapsulated materials. An additional advantage of these tapes is that they will not bond again after triggering.

Initial experiments with commercially available temperature-sensitive tapes containing thermoplastic expandable microspheres demonstrated their ability, after 1 week of bonding, to release when triggered from the plastics acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polyethylene terephthalate (PET), polypropylene (PP), and the copolymer ABS/PC and when triggered from painted steel. Only from aluminum, this tape did not release upon trigger temperatures of 130 °C. Additional experiments also demonstrated that a temperature of 130 °C is too high to be used for nondestructive disassembly of electronic products, since the softening temperature of the commonly used PC/ABS housing plastic for electronics is around 112 °C. As a result, the plastic components deform during triggering, which impedes the reuse of the plastic components, as shown in Fig. 1.

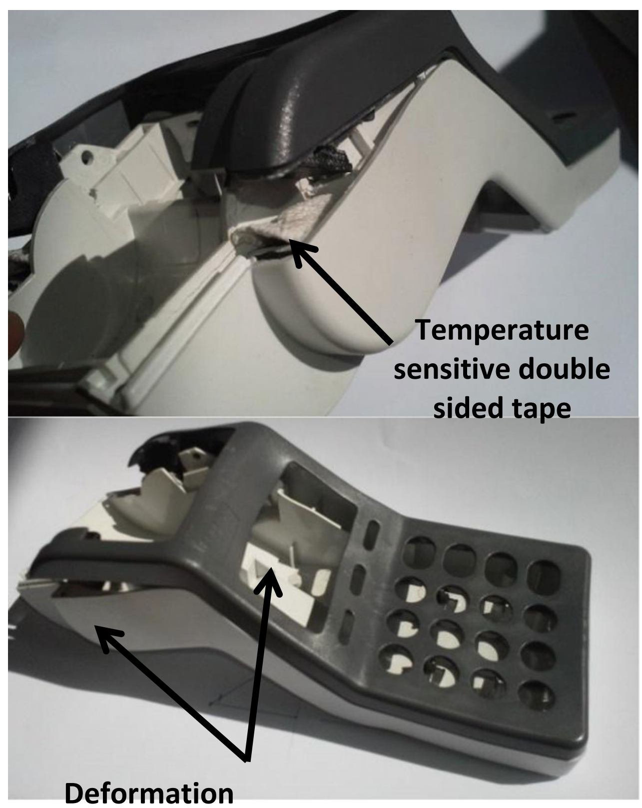

Fig. 1 Deformed merchant unit of a payment terminal after triggering of the temperature-sensitive tape

In general, there is only a very narrow temperature range which can be used to initiate a nondestructive disassembly process for electronic products, since the surrounding temperature can, in extreme conditions, almost reach the temperature at which electronic components start to fail, as indicated in Table 1. In addition, a temperature-triggered disassembly process is typically slow and can only be accelerated by submersion of the product in a hot liquid, since fasteners are often insulated by the product housing [36]. Furthermore, it should be considered that electronic components typically produce heat when functioning, which could cause accidental triggering. Another disadvantage of using temperature as a trigger is that a substantial amount of energy is required for heating up electronic products above the upper limit of the temperature range of the use phase of these products. For example, to heat up a flat screen TV with an average material composition from 20 to 95 °C, approximately 1.3 MJ of energy is required [9]. Hence, it can be concluded that a temperature increase is not a robust and efficient trigger for nondestructive AD. For this reason, no further experiments were performed with temperature-sensitive fasteners.

On the other hand, temperature-sensitive tapes and glues, commonly referred to as hot-melt adhesives or glues, are nowadays commonly applied in electronics, such as the Apple MacBook Air notebook and the HTC Desire smartphone. It should be noted that these are examples of active dismantling and not AD, since specific components are destroyed during the dismantling process, as the required trigger temperature is higher than the maximum failing temperature of the printed wiring boards (PWBs) embedded in the products. It should also be considered that these hot-melt adhesives and glues already partially release when gently heated. In addition, hot-melt adhesives do not completely release when intensively heated and re-bond when cooled down. This means that, for AD, the attached components need to be pulled apart during triggering. These hot-melt adhesives can also be seen as examples of design-embedded disassembly, since they require physical contact of the disassembly tool to initiate the disassembly process [25]. Accordingly, these hot-melt adhesives and glues can, for the purpose of repair or remanufacturing, only be released when a disassembly tool is accurately positioned relative to the product to locally heat the fasteners. However, for the purpose of material recycling, these hot-melt adhesives or glues can also be collectively triggered.

2.2 Electromagnetic RF waves

Prior research has demonstrated the feasibility of using radio frequency (RF) waves for wireless energy transfer over a distance of up to 2 m with an efficiency of approximately 40 % [37], which was achieved by making use of the principle of resonant inductive coupling [26]. Since this principle has been applied for recharging electronic products, specific RF waves could also be applied as a nondestructive trigger for AD. Within the presented research, a test setup was constructed, in which an electrical circuit, consisting of a planar circular receiving coil with an inductance of 29 μH, a capacitor of 227 nF, and a resistance wire of 8 Ω, was electrically connected, resulting in a resonance frequency of 62 kHz. In addition, a planar circular emitting coil with an inductance of 28.3 μH was electrically coupled to a capacitor of 233 nF and a function generator and amplifier. This system produced a 62-kHz sine wave signal of 30 V and 20 W. When these two coils were placed parallel at a distance of 20 mm, the electromagnetic energy was transferred with an efficiency of 45 %. This energy was converted into heat by a resistance wire, which in its turn successfully triggered a temperature-sensitive tape that retained the assembly.

Tests performed with this setup demonstrated that the efficiency at which the energy was transmitted rapidly decreased below 5 % when the receiving coil was placed under an angle of more than 60° with the transmitting coil or when a metal component or PWB was placed closer than 10 mm from the receiving coil. The energy transmission energy also dropped below 5 % when the transmitting and receiving coils were placed in parallel at a distance of 60 mm, which is due to the relative small outer diameter of approximately 100 mm of both coils. Because of the need for accurate positioning to reach adequate efficiency and because electronic products always contain a PWB that might adversely affect the energy transmission efficiency, it was concluded that the applicability of RF electromagnetic waves as a trigger for AD is limited for electronic equipment.

2.3 Pressure

A pressure increase or decrease of the surrounding air has been evaluated as a trigger with high potential for AD in prior research [38]. In order to evaluate the destructiveness of pressure for electronic components, an experiment was set up in which all PWBs of an LCD TV and a complete notebook were exposed to an overpressure of 7 bar for 10 min and to a nearly vacuum of <0.1-bar absolute pressure. Since both the LCD TV and the notebook were evaluated to retain full functionality, the experiments demonstrated that a pressure increase of up to 7 bar and a pressure decrease to 0.1 bar are not destructive for these electronic products.

An advantage of using pressure as a trigger for AD is that it requires substantially less energy compared to heating up an electronic product above the max temperature of its use phase. For example, increasing the air pressure around an average flat screen TV from 1 to 2 bar only requires 20-kJ energy, which is 800 times less compared to heating up similar products above the maximum product temperature acceptable during the use phase. In addition, there is a very low chance of accidentally triggering pressure-sensitive active fasteners, since pressure increases or drops during the lifetime of an electronic product are very limited.

3 Active fastener design

The following three principles can be used to develop embodiments for fasteners which can release as a result of changes in surrounding conditions: fasteners that can release by deformation, fasteners that can release due to a change in adhesion or cohesion forces, and fasteners that can release by a change in a certain field, for example, a change in a magnetic field. Since the previous section identified pressure as the trigger with the highest potential for robust, nondestructive AD, multiple physiochemical working principles that could initiate one of the prior mentioned actions as the result of a pressure increase or drop were explored within the presented research.

3.1 Fasteners sensitive to a pressure decrease

In line with the trend "object segmentation" of the problem solving, analysis, and forecasting tool "TRIZ" [39], the use of a vacuum is explored for the development of active fasteners. The advantage of the use of a vacuum is that a contact area of 1 cm^2 under vacuum condition can already retain two components with a force of approximately 10 N, when these components are subject to external atmospheric pressure. When the vacuum is broken or the surrounding air pressure is lowered to the pressure inside the vacuum, the forces, which retain the components, disappear. The main advantage of using a vacuum is that a vacuum neither requires space nor materials. However, one of the main challenges to develop robust vacuum-based fasteners is to maintain the vacuum within the fastener over the lifetime of the product in which the fasteners are applied. To maintain the vacuum, a so-called "getter" could be applied which is a component that contains a reactive material that either absorbs or chemically reacts with the penetrated air. Nevertheless, the long-term robustness of fasteners containing a vacuum cannot be assured, since all materials are permeable for gasses to some extent [40] and because getters only have limited absorption capacity. Initial prototypes of vacuum-based fasteners also confirmed the long-term instability of fasteners containing a vacuum.

Besides a vacuum, also a cavity that contains a specific amount of gas can be triggered by the application of a vacuum, since the gas within the cavity will expand proportionally to the decrease in the surrounding gas pressure. Active fasteners were developed which exploit this principle, as shown in Fig. 2. In the presented embodiment, the cavity will retain a U-profile, which holds two components together at atmospheric ambient air pressure. When placed in a vacuum environment, the cavity will expand, pushing away the U-profile and unlocking the attached components. Initial experiments

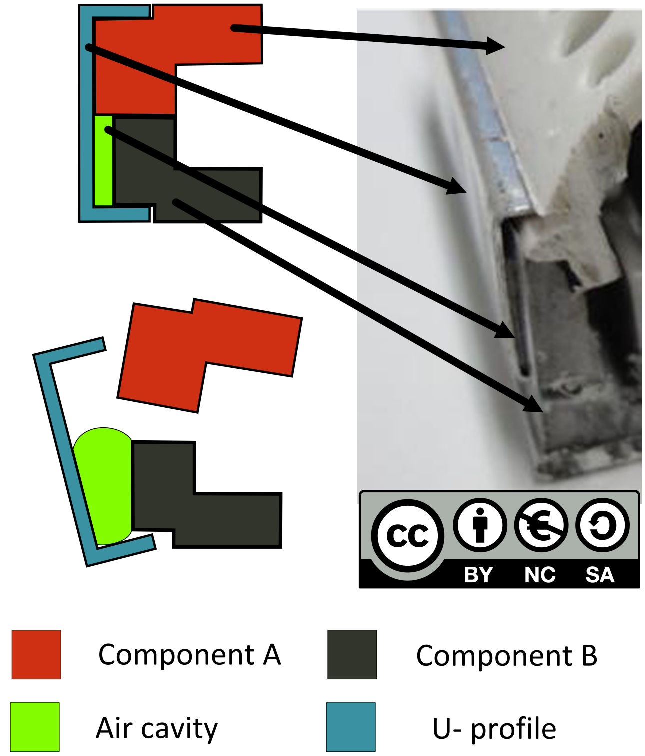

Fig. 2 Example of a vacuum-triggered active fastener

with prototypes similar to those shown in Fig. 2 demonstrated a high robustness and holding force of the presented active fasteners, but also indicated that the expansion forces of the cavity were, in some cases, too low to release the fasteners. Consequently, these fasteners require that both the fasteners and components are produced and assembled with high accuracy, which is likely to result in high production and assembly costs.

3.2 Fasteners sensitive to pressure increase

Active fasteners can also be conceived with a cavity that contracts when the ambient air pressure increases. Active fasteners with this working principle have been developed in prior research, and the first fasteners with this working principle were patented in 1990 [41, 42]. The main advantage of this working principle is its robustness due to the high stability of these fasteners over time and because high forces can be exerted by the application of an increased external air pressure. In prior research, different embodiments have been explored, and by means of 2-D topology optimization, a 2-D optimized shape was developed for a pressure-sensitive snap-fit [38, 43, 44]. In collaboration with Philips, this shape was further improved by implementing 3-D plastic hinges in the snap-fit design. The feasibility of releasing this fastener at an overpressure of 2 bar was demonstrated with a prototype built with stereolithography [45]. However, industrial implementation of this fastener design was hindered by the relatively large volume of 30×30×35 mm that is minimally required to include this fastener in an assembly.

For the development of the next generation of pressure-sensitive fasteners, the TRIZ trend “space segmentation” has been taken into consideration. This trend indicates that products will evolve from a monolithic system to a system with a cavity, to a system with multiple cavities. In accordance with this trend, snap-fits are developed with a closed-cell elastomer foam, which contracts under increased surrounding pressure and causes a deformation to unlock a geometrical interlock.

To evaluate the contraction forces that can be applied by a closed-cell foam, a test setup was constructed with a self-calibrated single point load cell (Tedea Huntleigh model nr. 1022) and an electronic pressure transducer (Druck model PMP 1400) (Fig. 3). Several experiments were carried out to identify the influence of the foam structure, material, and shape, on the foam performance, and to obtain better insights into the magnitude of the forces that will be generated within the developed active fasteners. For the first experiment, samples of 45×25×12 mm were cut with a hot-wire cutter from the following commercially available closed-cell foams: noncross-linked medium-density polyethylene (MDPE) foam with a density of 35 kg/m^3 (1), cross-linked metallocene polyethylene (MPE) foam with a density of 15 kg/m^3 (2), cross-linked low-density polyethylene (LDPE) foam with a density of 30 kg/m^3 (3), and cross-linked ethylene vinyl acetate (EVA) copolymer with a density of 35 kg/m^3 (4). These foams were selected because of their low density, high material elasticity, and small cell structure. This combination of properties enables to deliver optimal contraction forces, due to the limited energy required for material deformation and the maximum presence of intact and closed cells in the foam samples. Furthermore, also a foam sample with the same dimensions was produced from a two-component silicon with blowing agents and good skin formation properties (5). For all foam samples, the contraction forces were recorded at a sample frequency of 2 Hz as a function of the ambient air pressure which was increased with a velocity of around 1 bar per minute.

The results of these experiments, shown in Fig. 4, demonstrate that the performance of the foams made of cross-linked elastomers is significantly higher than the performance of the noncross-linked sample and that the self-produced foam performs poorly. The difference in performance can be explained by the lower porosity of the cross-linked foam samples. Based on the presented results, it was decided to use the cross-linked MPE closed-cell foam for further experiments, because of its outstanding performance at 2 bar and the low density of 15 kg/m^3 compared to the other foams, which enables the foam to contract more compared to the foams with a higher density.

In a second series of experiments, the contraction force was measured as a function of the ambient air pressure for multiple MPE foam samples with a height in the direction of contraction of 5 mm; a width of 8 mm; and different lengths of, respectively, 10, 15, 20, and 30 mm. The results of the contraction force measurements for foam samples with different lengths, shown in Fig. 5, demonstrate that the contraction force does not increase linearly with the surface of the foam sample perpendicular to the direction of contraction of the foam. This can be explained by the proportionally smaller section area for smaller foam samples, as a result of necking, as can be noticed in Fig. 3.

In a third series of experiments, the contraction force was measured for the largest foam sample as a function of the ambient air pressure after, respectively, 20, 40 and 60 % contraction. The results of these experiments, shown in Fig. 5, demonstrate that, at 6 bar, the contraction force decreases by approximately 50 % when the foam contracts 20 %. When the foam contracts 40 %, the contraction force will only lower to a limited extend and, afterward, rapidly drops to nearly zero

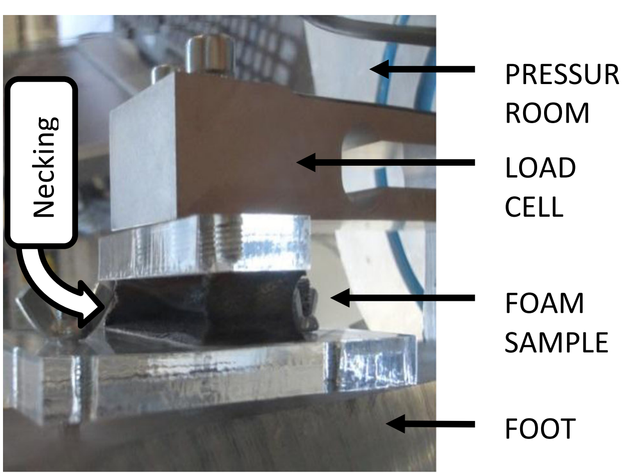

Fig. 3 Test setup for measuring contraction force of foam

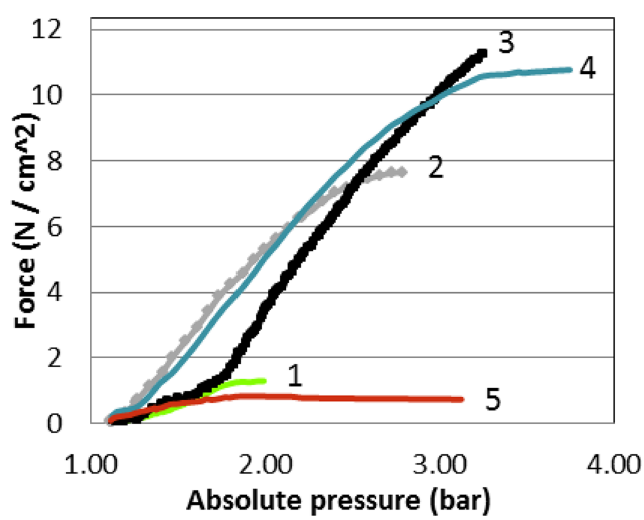

Fig. 4 Contraction force of different closed-cell elastomer foams at increasing ambient pressure (foam size *L* 45×*W* 25×*H* 12 mm, *1*: noncross-linked MDPE, *2*: cross-linked MPE, *3*: cross-linked LDPE, *4*: cross-linked EVA, and *5*: self-made silicon foam)

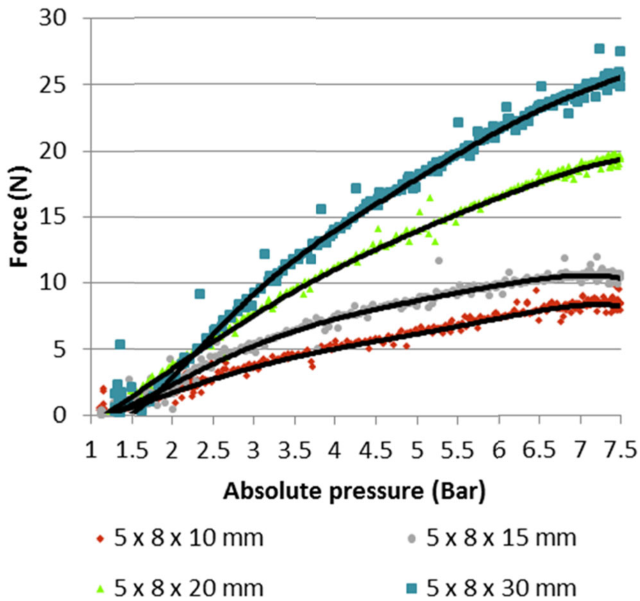

Fig. 5 Contraction force as a function of the ambient air pressure for different foam sizes

when the foam contracts 60 % (Fig. 6). This rapid decrease of the contraction force is due to a fast decrease of the section area of the foam as a result of necking when the foam contracts to a limited extend. When the foam contracts more, this only results in a limited additional decrease of the section area, which explains the stabilization of the contraction force. Finally, when the foam is contracted to a high extend, larger forces are required to compress the foam material, which explains the rapid drop in contraction force. Hence, it can be concluded that a small MPE closed-cell foam can initially execute significant contraction forces and is able to execute substantial forces after partial contraction. This is likely to

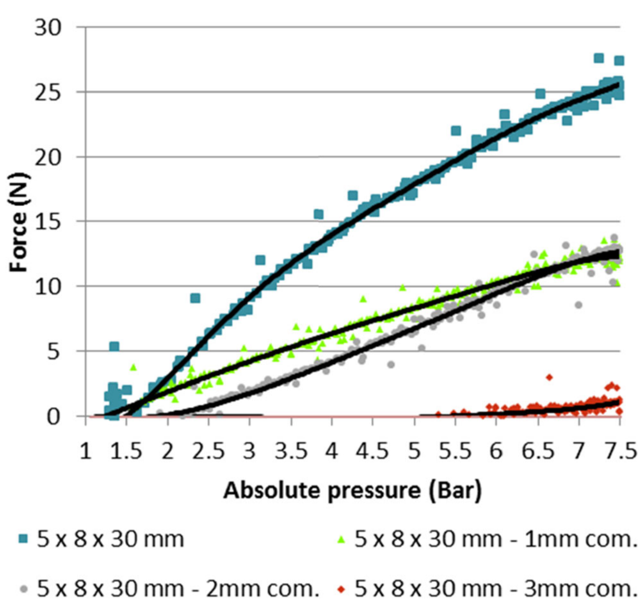

Fig. 6 Contraction force as a function of the ambient air pressure after, respectively, 20, 40, and 60 % contraction of the foam sample

facilitate the unlocking of a snap-fit, because high forces are initially required to overcome the static friction and, afterward, lower forces to overcome dynamic friction for the complete unlocking of the snap-fit.

In further experiments, the contraction force was measured for the MPE closed-cell foam while it was exposed to ten cycles of increasing and decreasing surrounding air pressure. Results of these experiments indicated no significant decrease in performance. Therefore, it can be concluded that consecutive compression of the foam and, accordingly, repetitive triggering of a pressure-sensitive foam-based fastener are possible, as required when a product needs to be disassembled multiple times over its life cycle, for example, for the purpose of repair and recycling.

3.3 Embodiments for fasteners sensitive to pressure increase

Multiple embodiments of fasteners which release at an increased ambient air pressure were developed, as shown in Fig. 7. The design process for these fasteners was an alternation of idea generation by using brainstorming, TRIZ and design-by-analogy techniques, and systematic evaluation of the generated ideas by means of functional prototypes, which were evaluated by multiple expert panels. In addition, the developed embodiments were analyzed based on axiomatic design to verify whether the independence axiom was fulfilled.

In an initial stage, fasteners were constructed similar to the product-integrated snap-fit developed by Neubert et al. [46] and the standalone snap-fit developed by Willems et al. using topology optimization [20, 38, 45]. Of these fasteners, the single cavity was replaced by the closed-cell foam. Some of the initial prototypes making use of a closed-cell foam and with a structure similar to the fastener developed by Willems et al. only released at pressure increases of more than 6 bar, and others even did not release at a pressure increase of 10 bar. Therefore, the design was further decoupled in accordance with the independence axiom by changing the design in such a manner that deformation of the snap-fit itself is no longer required to release the assembly [47, 48]. An additional advantage of the closed-cell elastic foam is that it can also be used in a fastener to clamp the attached components, while allowing sufficient play between the fastener and the attached components to facilitate the unlocking when a pressure increase is applied. Therefore, an additional foam was placed between component B and either the snap-fit or component A, as shown in Fig. 7 (4 and 5).

Besides snap-fit fasteners, also other pressure-sensitive foam-based fasteners were developed, as shown in Fig. 7 (1, 2, and 3). Initial prototypes demonstrated that these active fasteners are characterized by a limited holding force. To increase the holding force, the application of foams with a high

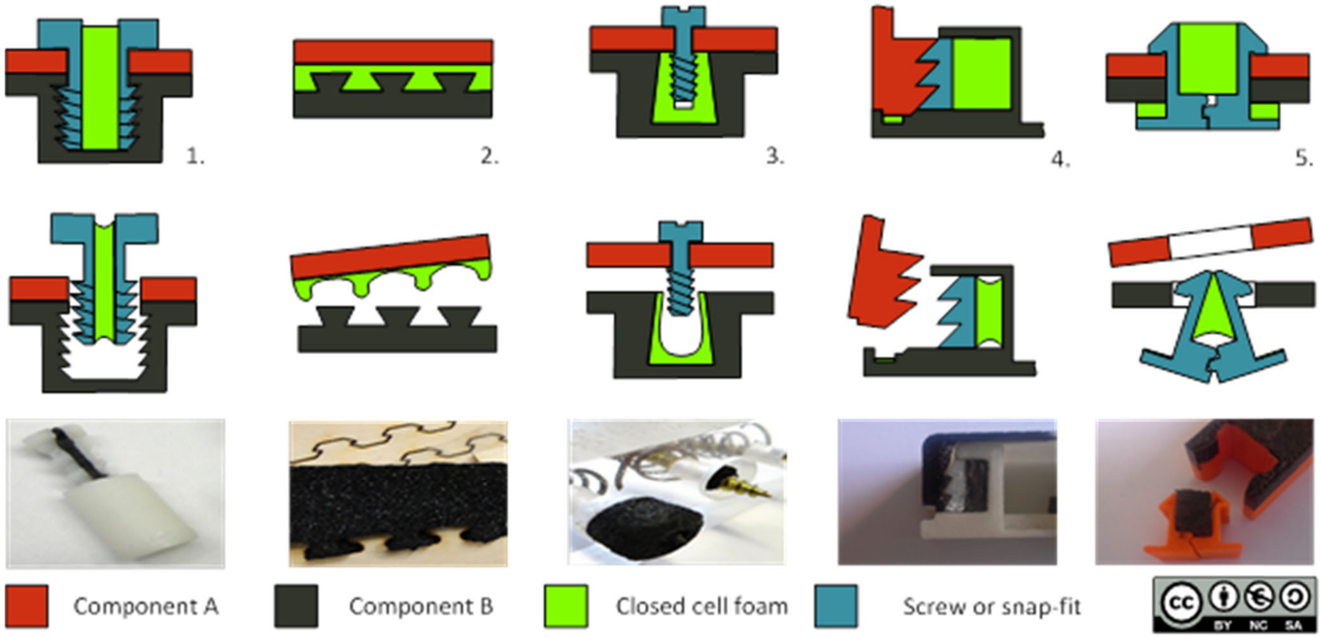

Fig. 7 Embodiments of foam-based fasteners sensitive to a pressure increase: *1*: Screw with foam center, *2* dovetail-shaped foam, *3* foam plug for screw, *4* product-integrated snap-fit, and *5* standalone snap-fit

stiffness would be required, whereas high-elasticity foam material is required to enable the contraction of the foam. One possibility to decouple these designs in accordance with the independence axiom is to use foams produced from temperature-sensitive materials of which the elasticity increases at elevated temperatures. An additional advantage of the application of temperature-sensitive foams, which requires the combination of multiple trigger signals to deform, is that the chance of involuntary disassembly will be lowered. Nevertheless, no further experiments were performed with temperature-sensitive foams, since the embodiments shown in Fig. 7 (4 and 5) are expected to be sufficiently robust and suitable for use in current electronics.

3.4 Evaluation of the foam-based fasteners

To evaluate the robustness of the pressure-sensitive fasteners, a standalone snap-fit was used to attach two plastic components that could be clamped in a standard tensile strength tester, as shown in Fig. 8. The prototype fastener was produced from ABS by means of fused deposition molding (FDM) and glued onto cross-linked MPE closed-cell foam with a density of 15 kg/m^3 of L 10 × W 8 × H 5 mm. The results of this tensile strength test, shown in Fig. 9, demonstrate that a single snap-fit can resist a force of approximately 200 N at which the snap-fit hooks will start to deform (Fig. 9: test 1). After release, the stand-alone snap-fit can be used to reassemble both components. However, the holding force of the fastener is lowered to approximately 150 N as a result of plastic deformation of the ABS (Fig. 9: test 2).

To further demonstrate the robustness and applicability of the developed pressure-sensitive fasteners, prototypes of the standalone and product-integrated foam-based snap-fits were implemented in a modem and in a merchant unit of a payment terminal, which are examples of small electronic products that are used in PSS business models in either a business to consumer or a business to business market. Both products are equipped with a design-embedded hinge system for the attached housing components, which leaves only one degree of freedom. This last degree of freedom was, in both products, locked by the implementation of two symmetrically placed foam-based snap-fits, as shown in Figs. 10 and 11.

To evaluate the robustness of the implemented foam-based fasteners, a pull force of 50–100 N was applied where possible on the housing components with a hook of a metal bar with a diameter of 5 mm, as shown in Fig. 12. In this manner, the force that could be manually applied on the product was

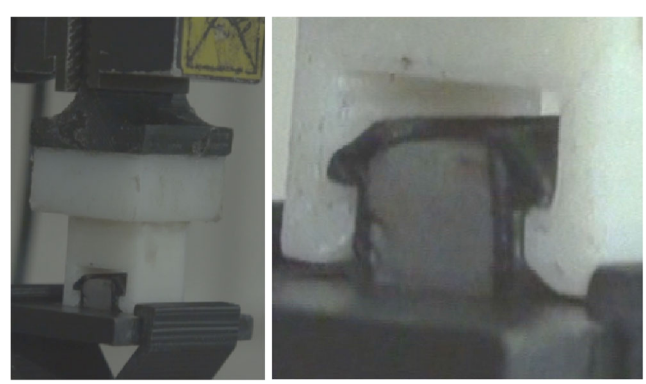

Fig. 8 Tensile strength test of a prototype of a pressure-sensitive standalone snap-fit

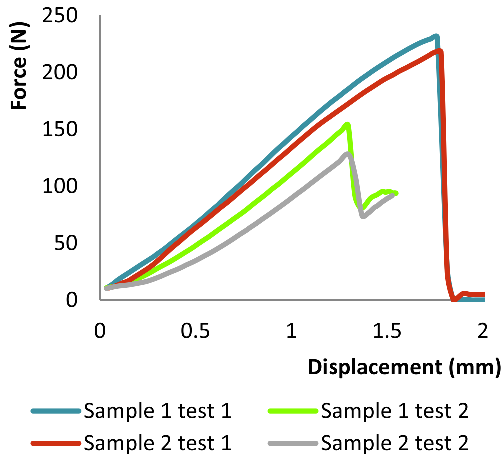

Fig. 9 Results of tensile strength tests performed on two prototypes of pressure-sensitive standalone snap-fits

simulated. Results of these experiments confirm the satisfactory robustness of the developed fasteners.

Afterward, both the modem and the merchant unit were submitted to an increased ambient pressure of 2-bar overpressure, which caused the active fasteners to simultaneously release. The components can be disassembled after unlocking of the fasteners by shaking the product or by inserting a spring in the product design, which will cause the product to pop open when triggered. After disassembly, all components can be handpicked and sorted. Afterward, the pressure-sensitive snap-fits are likely to remain fixed or to end up in the same fraction as the plastic components. However, the foam-based fasteners can be easily separated from the housing plastics in a density-based separation process, such as a sink-float process, which is commonly applied to separate and purify different plastics originating from WEEE.

For larger-scale implementation of these fasteners, a co-extrusion process could be used, for example, as used for the extrusion of a coated flexible polyethylene (PE) foam, or a multiple cavities injection molding process can be used, which is commonly used for the production of temperature-resistant seals from flexible polyurethane foam integrated in plastic

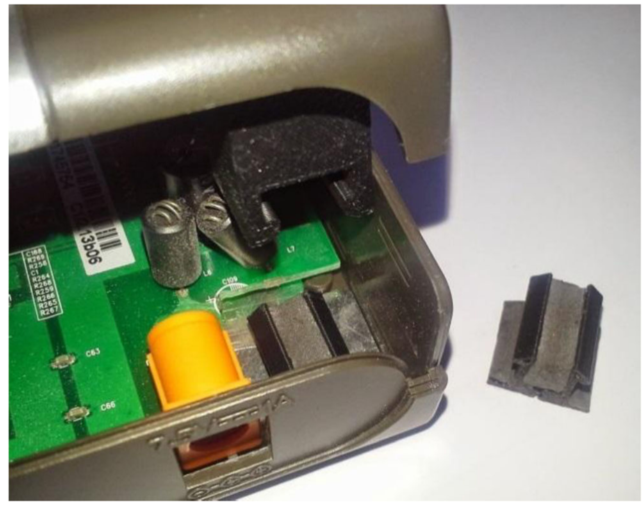

Fig. 11 AirPlus WiFi modem of D-Link equipped with standalone pressure-sensitive foam-based snap-fits

components [49]. Since these production processes are often applied for low-cost products of which the foam needs to remain flexible over a long period of time while withstanding high variations in surrounding temperature, it can be expected that these processes can also be used to produce durable active fasteners at low cost.

4 Conclusions and outline for future research

Within prior research, it was demonstrated that disassembly is a crucial step in repair, reconditioning, and remanufacturing operations and that it allows recycling EoL electronic equipment with a higher efficiency from both an economic and environmental perspective. Therefore, novel active fasteners, which have the potential to significantly reduce disassembly costs, were developed in the presented research.

Results of the performed experiments demonstrated that the contraction force of the applied closed-cell foams can reach up to 6 N/cm^2 at an overpressure of 2 bar. Furthermore, it was demonstrated that the foam-based snap-fits can easily

Fig. 10 Merchant unit accessory to the Yomani payment terminal of Atos Worldline with integrated pressure-sensitive foam-based snap-fits

Fig. 12 Pull forces applied on by foam-based fasteners to attached housing of the merchant unit

be implemented in small electronic products and that an overpressure of 2 bar can initiate the AD process. In addition, it was demonstrated that the developed fasteners have a high robustness and can resist a pull force of up to 200 N.

To further promote the industrial implementation of the developed active fasteners, ongoing research focuses on quantifying how product design improvements can create both opportunities for OEMs and society from an economic and environmental perspective. Furthermore, to allow manufacturers and recyclers to jointly benefit from product improvements, new business models are being explored in which manufacturers and recyclers can closely cooperate.

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References

1. Umeda Y, Takata S, Kimura F, Tomiyama T, Sutherland JW, Kara S, Herrmann C, Duflou JR (2012) Toward integrated product and process life cycle planning—an environmental perspective. CIRP Ann Manuf Technol 61(2):681–702. doi:10.1016/j.cirp.2012.05.004
2. Boothroyd G, Alting L (1992) Design for assembly and disassembly. CIRP Ann Manuf Technol 41(2):625–636. doi:10.1016/S0007-8506(07)63249-1
3. Alting DL, Jøgensen DJ (1993) The life cycle concept as a basis for sustainable industrial production. CIRP Ann Manuf Technol 42(1): 163–167. doi:10.1016/S0007-8506(07)62417-2
4. Sundin E Product and process design for successful remanufacturing, 2004 Linköpings Universitet
5. Yang SS, Ong SK, Nee AYC (2014) EOL strategy planning for components of returned products. Int J Adv Manufac Technol: 1–13. doi:10.1007/s00170-014-6505-0
6. Yang Q, Yu S, Sekhari A (2011) A modular eco-design method for life cycle engineering based on redesign risk control. Int J Adv Manuf Technol 56(9–12):1215–1233. doi:10.1007/s00170-011-3246-1
7. Meskers C, Hagelüken C, Salhofer S (2009) Impact of pre-processing routes on precious metal recovery from PCs. Paper presented at the European Metallurgical Conference (EMC) Innsbruck, Austria
8. Peeters JR, Vanegas P, Tange L, Van Houwelingen J, Duflou JR (2013) Closed loop recycling of plastics containing flame retardants. Res Conserv Recyc 84:36–43
9. Peeters JR, Vanegas P, Duflou JR, Mizunoc T, Fukushigec S, Umeda Y (2013) Effects of boundary conditions on the end-of-life treatment of LCD TVs. CIRP Ann Manufac Technol 62(1): 35–38
10. Willems B, Dewulf W, Duflou J (2005) Design for active disassembly (DfAD)—an outline for future research. Paper presented at the IEEE International Symposium on Electronics & the Environment
11. Duflou JR, Willems B, Dewulf W (2006) Towards self-disassembling products—design solutions for economically feasible large-scale disassembly. Innovation in Life Cycle Engineering and Sustainable Development: 87–110
12. Boothroyd G (1987) Design for assembly—the key to design for manufacture. Int J Adv Manuf Technol 2(3):3–11. doi:10.1007/bf02601481
13. Chang T-R, Wang C-S, Wang C-C (2013) A systematic approach for green design in modular product development. Int J Adv Manuf Technol 68(9–12):2729–2741. doi:10.1007/s00170-013-4865-5
14. Seliger G, Basdere B, Keil T, Rebafka U (2002) Innovative processes and tools for disassembly. CIRP Ann Manuf Technol 51(1): 37–40. doi:10.1016/S0007-8506(07)61460-7
15. Torres F (2004) Automatic PC disassembly for component recovery. Int J Adv Manuf Technol 23(1–2):39
16. Kim HJ, Kernbaum S, Seliger G (2009) Emulation-based control of a disassembly system for LCD monitors. Int J Adv Manuf Technol 40(3/4):383–392. doi:10.1007/s00170-007-1334-z
17. Basdere B (2003) Disassembly factories for electrical and electronic products to recover resources in product and material cycles. Environ Sci Technol 37(23):5354
18. Kopacek P, Kopacek B (2006) Intelligent, flexible disassembly. Int J Adv Manuf Technol 30(5–6):554–560. doi:10.1007/s00170-005-0042-9
19. Schumacher P, Jouaneh M (2013) A system for automated disassembly of snap-fit covers. Int J Adv Manuf Technol 69(9–12): 2055–2069. doi:10.1007/s00170-013-5174-8
20. Duflou JR, Seliger G, Kara S, Umeda Y, Ometto A, Willems B (2008) Efficiency and feasibility of product disassembly: a case-based study. CIRP Ann Manuf Technol 57(2):583–600. doi:10.1016/j.cirp.2008.09.009
21. Merdan M, Lepuschitz W, Meurer T, Vincze M Towards ontology-based automated disassembly systems. In: IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society, 7–10 Nov. 2010. pp 1392–1397
22. Weigl-Seitz A, Hohm K, Seitz M, Tolle H (2006) On strategies and solutions for automated disassembly of electronic devices. Int J Adv Manuf Technol 30(5–6):561–573. doi:10.1007/s00170-005-0043-8
23. Lee SG, Lye SW, Khoo MK (2001) A multi-objective methodology for evaluating product end-of-life options and disassembly. Int J Adv Manuf Technol 18(2):148–156. doi:10.1007/s001700170086
24. Pretsch T (2010) Review on the functional determinants and durability of shape memory polymers. J Polym 2(3):120
25. Willems B (2007) Doctoral dissertation: development of improved fastening techniques in support of design for disassembly strategies. KU Leuven, Leuven, ISBN: 978-90-5682-822-6
26. Tesla N, James Clerk M (2011) Wireless power transfer technology and EV application
27. Chiodo JD, Billett EH, Harrison DJ (1999) Active disassembly using shape memory polymers for the mobile phone industry. Ieee Int Symp Electr 151–156:344
28. Chiodo JD, Harrison DJ, Billett EH (2001) An initial investigation into active disassembly using shape memory polymers. P I Mech Eng B-J Eng 215(5):733–741
29. Chiodo JD, McLaren J, Billett EH, Harrison DJ Isolating LCD's at end-of-life using active disassembly technology: a feasibility study. In: Proceedings of the 2000 Ieee International Symposium on Electronics and the Environment, 2000. pp 318–323, 359
30. Chiodo JD, Billett EH, Harrison DJ Preliminary investigations of active disassembly using shape memory polymers. In: First International Symposium on Environmentally Conscious Design and Inverse Manufacturing, 1999. pp 590–596, 1021
31. Chiodo JD, Jones N, Billett EH, Harrison DJ (2002) Shape memory alloy actuators for active disassembly using 'smart' materials of consumer electronic products. Mater Des 23(5):471–478
32. Nick Jones DH, Hussein H, Billett E, Chiodo J (2003) Towards self-disassembling vehicles. J Sustain Prod Des 3(1):59–74
33. Arnaiz S, Bodenhoefer K, Harrison D, Herrmann C, Hussein H, Irasarri L, Malaina M, Schnecke D, Tanskanen P (2004) 'Active disassembly using Smart Materials' End of Life technology for

WEEE—results from the framework V project. Electronics Goes Green 2004 (Plus): driving forces for future electronics, Proceedings: 275–280, 1092
34. Bain P, Manfre G (2006) Method and apparatus for bonding and debonding adhesive interface surfaces. US Patent
35. Cingil HE (2010) Conducting polymer-coated thermally expandable microspheres. Polym Chem 1(8):1323
36. Carrell J (2010) Robust analysis of the active disassembly process. Paper presented at the IEEE International Symposium on Sustainable Systems and Technology
37. Kurs A (2007) Wireless power transfer via strongly coupled magnetic resonances. J Sci 317(5834):83
38. Willems B (2007) Development of improved fastening techniques in support of design for disassembly strategies. Katholieke Universiteit Leuven, Leuven
39. Savransky SD (2000) Engineering of creativity: introduction to Triz methodology of inventive problem solving. CRC Press, Boca Raton
40. Prokhorov AM (1970) Great Soviet Encyclopedia
41. Pugliesi-Conti J, Girardiere C (1990) Snap-fit device for joining two parts together US005102253A
42. Kott N (2003) Fastener system. US2003/0044229
43. Willems B, Dewulf W, Duflou JR (2007) Active snap-fit development using topology optimization. Int J Prod Res 45(18–19):4163–4187. doi:10.1080/00207540701440311
44. Willems B, Dewulf W, Duflou JR (2007) Pressure-triggered active fasteners: design results using topology optimization. Proceed 2007 I.E. Int Sympos Electron Environ, Conf Rec 184–189:262
45. Van Horenbeek A, Albert-Nagy A (2009) Pressure-based fastener optimization and implementation in a Philips flat screen TV. KU Leuven, Leuven
46. Neubert H (2000) Simultan lösbare Verbindungen zur Rationalisierung der Demontage in der Feinwerktechnik. Technical University of Dresden
47. Peeters JR, Van den Bossche W, Devolder T, Dewulf W, Duflou JR (2014) Second generation of pressure sensitive fasteners for active disassembly. Paper presented at the 21st CIRP Conference on Life Cycle Engineering, Norway, Trondheim
48. Suh NP (1998) Axiomatic design theory for systems. Res Eng Des 10(4):189–209
49. CeraCon (2013) S-FIT® (Soft foam injection technology). http://www.ceracon.com/