ARTICLE IN PRESS

Engineering Science and Technology, an International Journal xxx (xxxx) xxx

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Review

A review of advances in design for disassembly with active disassembly applications

Hoda Abuzied[a,*], Hesham Senbel[b], Mohamed Awad[b], Ayman Abbas[a]

[a] Mechanical Engineering Department, Faculty of Engineering, The British University in Egypt, El-Sherouk City, 11837 Cairo, Egypt
[b] Design & Production Engineering Department, Faculty of Engineering, Ain Shams University, Abbasseya, 11535 Cairo, Egypt

ARTICLE INFO

Article history:
Received 16 March 2019
Revised 31 May 2019
Accepted 9 July 2019
Available online xxxx

Keywords:
Design for disassembly
Active disassembly
Shape memory alloys
Shape memory actuator

ABSTRACT

The rapid changes in industry during the past decade, have started to greatly affect the manufacturing environment and production facilities. Traditional production facilities are being replaced by smart factories that are based on high technological aspects using smart machines to produce smart products. Due to the shortening of products life cycle, the need for a rapid design process has become an emerging issue.

However, the rapid design process is not the only challenge but also, speed and efficiency of the assembly process, after sale services and disassembly operations. Thus, design for disassembly has become an important sub-topic for the design process. As a result, product designers are now concerned with designing products that can be disassembled easily to avoid destructive separation of products, in order to minimize waste and scrap of products at their end of life. This can be done by allowing recovery of reusable components and materials so that they can be used in later generations of products, remanufacturing or recycling processes.

Design for disassembly offers different disassembly techniques that can facilitate the disassembly process greatly. Active disassembly is considered as one of the most important disassembly techniques. This is due to the fact; active disassembly can provide a more generic solution for most of disassembly problems as well be discussed in the present research. As a result, the present research aims to present an overview of design for disassembly discussing its different techniques with emphasis on active disassembly focusing on its importance and advances in detail.

Contents

* Corresponding author.
E-mail address: hoda.abuzied@bue.edu.eg (H. Abuzied).
Peer review under responsibility of Karabuk University.

https://doi.org/10.1016/j.jestch.2019.07.003
2215-0986/© 2019 Karabuk University. Publishing services by Elsevier B.V.

1. Introduction

Nowadays, the global demand for reducing expenses of energy and raw materials in the manufacturing process became a very emerging issue, which increased greatly the need for a more efficient products [1]. As a result, the market demands for enabling economic recycling of products and reducing the environmental impact at their End of Life (EOL) were increased. These demands can be satisfied by increasing the value of products at their EOL, through allowing the non-destructive separation of their components and materials, so that they can be used in later generations of products [2].

Disassembly approaches became a very important issue at the EOL of products [1]. Since; an efficient disassembly approach can improve life cycle behavior of products during their usage phase by facilitating maintenance and repair during service. Also, it promotes the recycling of products at their EOL through enabling recovery and reuse of components and materials [3]. Hence, the selection of the proper disassembly approach must be put into consideration during the early stage of design process to improve products sustainability [1].

In the past years, disassembly was considered as a disadvantageous EOL activity of products, since it was very difficult, time consuming and very expensive [4]. Many products were not repaired due to high dismantling costs required as these products were disassembled either manually or automatically. Manual disassembly requires the use of many tools by the operator and requires some time. Despite, little operator cost, and time required by automated disassembly, large financial investment in machines is essential [4]. Additionally, automated disassembly lines offer lower flexibility as; they may not reach various infrastructure of products easily [5]. Also, designers and producers have limited their efforts to develop products for easy manufacture and assembly while ignoring easy disassembly [6]. Hence, increased the possibility of products exposure to damage during the disassembly process. Resulting in reduction of the possibility of material recovery, an increase in the disassembly time, and an increase in the waste of products at their EOL [7]. As a result, Design For Disassembly (DFD) has become an emerging issue as it allows products to be dismantled easily [6].

2. Design for disassembly

Design for disassembly (DFD) is a design concept that designers use to facilitate the dismantling process of products [6]. Generally, DFD involves [8]:

1. Simplifying the de-manufacturing process,
2. Reducing needed time and cost for disassembly,
3. Allowing recovery of components and materials.

DFD can be considered as a type of green manufacturing term used to describe methods of producing environmental sound products. These products are designed to be disassembled for recovery of precious reusable materials and components, and for easier maintenance with a cost-effective separation. Thus, reduces waste and scrap of products at their EOL by allowing product reuse, remanufacturing and recycling [2].

DFD covers several design tasks such as selection of material, design of component and definition of product architecture, besides proper selection and usage of joints and fasteners [8]. Its techniques are implemented to allow companies take a product back from the EOL to the beginning, so that its components can be used in later generation of products [2].To ensure a successful implementation of DFD techniques, designers must consider several guidelines [3]:

1. Product architecture, design of its components, used fasteners and type of used material.
2. EOL destination for each component i.e. whether it will be recycled, reused or landfilled disposed with a regular or special treatment.
3. Revenue from each component based on its EOL destination.
4. Cost of labor for the disassembly process.
5. Cost of disposal of products waste remainders from each step in the disassembly process.
6. The resultant profit from every single step in the disassembly process.
7. Effect of every single step in the disassembly process.

Generally, parts and components can be dismantled using a single or combination of disassembly action. A one to one disassembly action involves removing of one fastener at a time [9]. While, one to many disassembly actions involves removal of various connections with one disassembly action. Economic models proved that, one to many disassembly technique reduces disassembly time and cost greatly [10].

2.1. DFD technologies

One to many disassembly techniques are being used to dismantle various connections with a one disassembly action under the effect of an external stimuli such as heat, electrical, mechanical ...etc. Hence, increases efficiency of the disassembly process. DFD techniques are divided into two categories: *disassembly embedded design* and *active disassembly* [9].

Disassembly embedded design consists of a mechanism for disassembly which is designed to be implemented into the product. This mechanism can be triggered to initiate the disassembly process using a thermal, electrical, mechanical or an electromagnetic stimuli [9]. While, active disassembly enables separation of assemblies using smart materials or structures in the product that can be activated using a single or more external stimuli [10].

Despite the great reduction in disassembly time offered by disassembly embedded design, it has several drawbacks. First, during implementation, the specific nature of disconnection for each product feature, requires a considerable amount of knowledge and time from the designer. Second, the reduction in disassembly time is limited because of the physical constraints that reduces the number of connections that can be linked to be unfastened at the same time with one disassembly action [10]. Third, each embedded device has a unique application feature for each product, as a result they cannot be used in other applications without considerable redesign efforts [11]. In addition, great efforts are required from the designers to implement the mechanism of disassembly into the product structure itself. Also, disassembly embedded product design can develop to be very difficult due to space and manufacturability limitations [9]. As a result, no drastic increase in disassembly efficiency can be guaranteed unless the physical contact is eliminated from the disassembly process [10]. Furthermore, extra costs during manufacturing cannot be ignored, which question the economic viability of this technique. All these reasons, made the shift for a more generic fastener type is an essential process [11].

Active disassembly technique offers a solution to most of these limitations. It offers a generic disconnecting solution for different disassembly problems as; it allows application of a single technique in various situations, thus reducing constrains for the product designer. In addition to the ability of linking an unlimited number of connections to be unfastened at the same time. Theoretically speaking, a single trigger can be sufficient to unfasten all connections [10]. As a result, the disassembly time is reduced greatly. Finally, the use of external triggers, eliminates the need for any physical contact during the process of disassembly. Thus, reduces

Please cite this article as: H. Abuzied, H. Senbel, M. Awad et al., A review of advances in design for disassembly with active disassembly applications, Engineering Science and Technology, an International Journal, https://doi.org/10.1016/j.jestch.2019.07.003

greatly or eliminates the need for any human effort in the unfastening of fasteners [11]. Also, the accessibility of fasteners is no longer an issue as mechanical tools are not needed for releasing or loosening fasteners [9]. All these factors led to a great ease in the disassembly process [10].

3. Active disassembly

Active Disassembly (AD) is a new field emerging in the research of product disassembly that allows cost effective, non-destructive and mass disassembly of products [4]. AD allows self-disassembly of products [12] using active joints and fasteners, which can be disassembled without a direct contact between the product and the labor [13]. Through, using external triggers or stimuli's such as temperature, magnetic force or pressure [9]. This is achieved through using shape memory effect (SME) of smart materials that is used for producing active joints and fasteners [12]. In addition, SME can be induced in the material by deforming the material in its martensitic phase causing a permanent inelastic strain upon unloading. Also, it can be triggered by heating the material to its austenite phase causing retrieval of initial shape of the material [14]. Also, the SME property is responsible for a fast, clean, efficient and non-destructive separation of complex product assemblies at its EOL [12], by allowing active fasteners restore their original shape [15].

AD is based on the concept of shape memory alloy (SMA) or shape memory polymer (SMP) that can spontaneously reverse back to their initial shape upon exposure to a specific circumstance using active disassembling devices. Active disassembly device is implemented in the products during their design and assembly stages. During products design phase, a suitable active disassembly device must be selected carefully based on the requirements of the products. To design a product based upon AD concept, the traditional design method must be applied at first to the initial device. The material must be selected according to the preliminary device and the surrounding environmental conditions. Finally, the active disassembly device can be designed and implemented in its suitable place to achieve AD [16].

A deformed SMA element can generate large recovery stress (400–480 MPa) with strain (6–8%) upon restoring its original form [17,18], based on chemical composition and main microstructural features of the alloy [19]. For example, a 15 mm diameter $\times$ 29 mm length NiTi cylinder compressed to 28 mm length can produce a force of 98 KN sufficient to break rocks upon exposure to a specific temperature with no sound or vibrations [20].

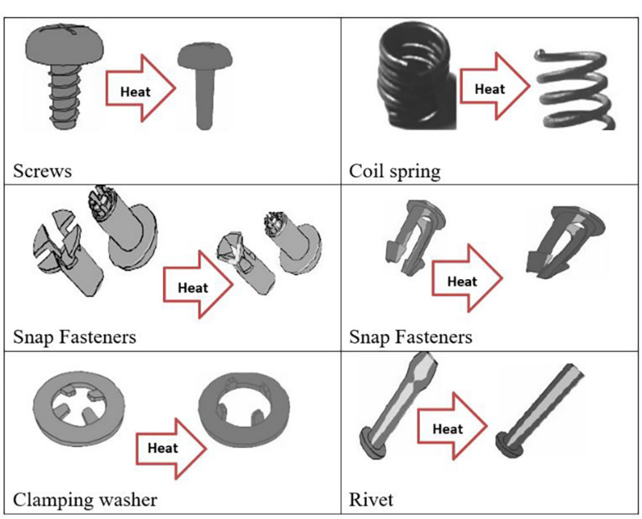

Fig. 1. Different forms of SMA/SMP active joints [13].

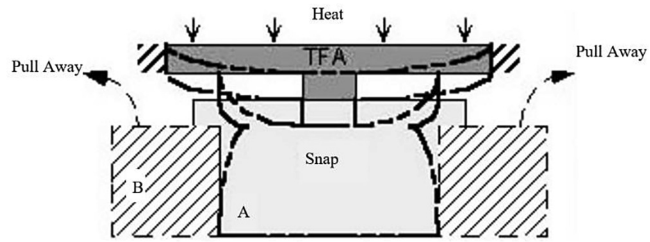

Fig. 2. Design concept of a heat activated snap-fit [21].

As a result, SMA can be used to produce active disassembly devices that generates actuating forces. These active devices can exist in the form of tube, cotter pin, splint pin, coil- spring, ribbon and rivets [16]. While, SMP element generate a very low recovery force with large deformation. Therefore, SMP can be used to produce active disassembly devices such as rivets, snap-fit, washer, screw, and zipper- snap fit [16]. Currently, there are two types of AD techniques based on type of active joint used to initiate the process of disassembly, joints based on properties of material or joints based on properties of structure [13].

Joints based on properties of material will be made of either SMA actuator devices or SMP releasable fastener devices to initiate the disassembly process. Any of these materials can change its shape into another predefined shape upon exposure to a specific temperature trigger. Fig. 1, illustrates different forms of SMA/SMP active joints that can return to their original shape upon exposure to a temperature higher than their triggering temperature. While, joints based on properties of structure uses geometry, shape and sometimes properties of material to initiate disjoining action that initiates disassembly of joint. For example, pneumatic snap fit that triggers upon exposure to an external pneumatic pressure to activate joint disassembly [13]. Fig. 2, illustrates an example of heat activated snap-fit, where A and B are two components that are locked together using a snap-fit. The heated part B acts as a thermal force applicator (TFA) which provides the necessary input force to deflect the unit A, causing the disengagement of the locking (deformation is shown by dashed lines) [21].

Recently AD is considered as an essential EOL product disassembly technique as; it can improve recovery opportunities by reducing costs associated with manual disassembly and maintaining value of quality of recovered product components by replacing conventional disassembly techniques. Reducing the environmental concerns that might occur due to the obligatory complete or partial disassembly of an EOL product containing hazardous materials that needs to be disassembled and isolated before shredding or incineration [13]. This technique is also useful for dismantling products having complex assemblies that are working under severe operating conditions such as very high temperature or vibration [22]. Finally, AD enables the development of fasteners having lower technical disassembly complexity that allows simultaneous release from products, thus significantly decrease the required disassembly time [23].

Despite, the advantages stated which make AD the most efficient EOL scenario, it has a few drawbacks. The common drawback for all materials used in AD is the possibility of occurrence of undesired accidental triggering of disassembly process during system operation. This is due to the fact that AD is a single trigger process, which makes control of the disassembly process by controlling duration and how heat is applied a very limited process [24]. Moreover, high investments or training might be required for some materials, which might question the economic feasibility of these methods. Finally, since the cost of extra investments needed to design the material into the product will be carried by the manufacturer, the beneficiaries of the efforts made might be questioned as the benefits are supposed to be gained by EOL treatment facilities only not the manufacturers [9,10].

Researchers have so far conducted many studies to come with solutions to overcome these drawbacks in order to promote AD. Zhang et al. [24,25], proposed a modification to avoid problems of undesired accidental triggering by making triggering of AD structures difficult under a single trigger field. AD was modified to activate under the effect of both a specific value of thermal and magnetic heat fields concurrently. Also, Zhifeng et al. [24,25], encouraged a technique of multiple triggering by activating AD under the effect of both a specific value of triggering temperature and pressure concurrently. These modifications AD structures have higher reliability during normal use as it must satisfy the temperature and pressure conditions concurrently to activate AD. As for doubts about benefits that can be gained by manufacturers for implementing AD, Peeters et al. [23], suggested that all different actors in the product life cycle should be involved. Thus, manufacturers or companies can considerably benefit from EOL strategy with AD, as they will be responsible for the EOL treatment of their products.

3.1. Design of active disassembly device

Design methodology is considered as the main key for a successful implementation of AD technology. Methods of designing AD must follow the following design criteria [25]:

1. The Structure of AD must not affect the performance of the product as users are concerned only about product performance. As a result, the characteristics of performance should be the basic characteristic of the whole design.
2. Accidental triggering of the product during normal operation must be avoided to prevent decreasing the reliability of products. In case of using single triggering field, triggering should be done using a temperature higher than normal temperature by 20 °C or a pressure having a triggering value higher than normal one by 100%. While, in case of using a combination of these two triggering fields, the disassembly process will not be activated if only one physical field reaches its triggering value. It will be activated only if both physical fields reach their triggering values concurrently.
3. The structure of AD must be kept as simple as possible and easy to be separated. As a result, the cost of AD device in the entire life cycle including design, manufacturing and disassembly can be reduced greatly using simpler AD structure design.

3.2. Smart materials in active disassembly

Smart materials have a great potential and a wide range of applications in facilitating self-disassembly [12]. They can sense any environmental change and respond to it in various dimensions [26]. They are used in designing releasable fasteners and actuators that can aid in a controlled, cost effective, hierarchical and non-destructive separation of products and components [12]. It includes many materials that can be used to facilitate AD such as engineering polymers, liquids and adhesives, bio-degradable layers, films, coatings and substances [27]. Shape memory alloys (SMA) and shape memory polymer (SMP) are considered as the most common types of smart materials. Both materials have two phases: martensite phase which is the low temperature phase and austenite which is high temperature phase. Also, they can alter their mechanical properties as a function of a temperature change. Thus, upon heating the material above a certain specified temperature, SME will occur causing recovery of the material to its original shape [15,28]. As a result, SME can be defined as the phenomena that is responsible for the ability of a severely and quasi-plastically pre-deformed material, to retrieve its initial shape at the presence of the proper stimulus [29].

SMA's are characterized by their ability to remember their original shape [30]. They can recover large deformations, produce high stresses and work outputs up to 12–18 J/cm^3 upon exposure to mechanical or thermal stimuli [19,31]. In general, the induced deformation in the material can be retrieved by applying heat above a specific value of temperature. Also, large forces can be generated upon application of heat to a deformed material that is constrained from recovering its original shape [31]. As a result, SMAs can be used as actuators and considered as a light weight alternatives for pneumatic or hydraulic actuators in automotive, aerospace and down-hole energy exploration industries [12,19]. SMA actuator devices can be either one way of nearly equal NiTi composition or two way devices typically made of Cu-based alloys [12,27]. Cu-based SMAs offers lower force application than that can be offered by NiTi SMAs per unit mass actuator applications [12]. One-way SMA actuator can only provide force/displacement in one direction. For example, an SMA wire that contracts upon heating to a specific temperature, does not expand to return to its cold shape upon cooling down the alloy spontaneously. Rather, an external force (i.e. a bias/return mechanism) is needed to return the actuator to its original cold shape after the heating phase [32]. While, two-way SMA actuator can remember one geometric shape at high temperature and another one at low temperature. As a result, upon repeated heating and cooling, SMA changes its shape between its corresponding high and low temperature shapes without any need for an external device i.e. no need for a bias mechanism [26]. However, the displacement produced is not as high as that in one way SMA actuator [32].

Generally, one-way SMA actuator offers a more reliable and economical solution than two-way SMA actuators. Due to the high training required for two-way actuators, their commercial availability is greatly reduced. Also, two-way actuators suffer from high strain deterioration rate especially at elevated temperatures [33].

SMAs exists in the form of alloys having different chemical composition such as copper-zinc-aluminium, iron-manganese-silicon, copper-aluminium-nickel, and nickel-titanium [18]. Even though, all these alloys exhibits SME, NiTi alloys is considered as the most useful SMA alloy and most preferred for most of applications [18,33]. This is due to the commercially availability of NiTi alloys, excellent mechanical properties including significant ductility and strain recovery under constrained conditions and also, adjustable shape memory properties using proper heat treatments [34]. On the other hand, other alloys such as iron based and copper based SMA alloys have poor thermomechanical performance, instable and impractical (e.g. brittle) [33]. Even though, each material finds its own advantage for a particular application or requirement [33]. For an example, Cu-based SMA alloys became an emerging potential substitute for NiTi alloy; due to their lower cost, superior thermal and electrical properties than that exhibited by NiTi alloys in addition to having mechanical properties similar to those of NiTi [35]. All these properties have led Cu-based SMA alloys to be considered for applications in vibration control systems and seismic devices [35]. Also, the higher stiffness of Cu based SMA alloys than that exhibited by NiTi alloys, made Cu based alloys a good candidate for medical guide wires that can be used for catheters that can be subjected to high rotation and bending in the blood vessel [36].

Equi-atomic NiTi alloy is the most useful and commercially available alloy among different types of SMA alloys for applications exhibiting operating temperature below 100 °C [18,19]. It is frequently referred as Nitinol in reference to Nickel Titanium Naval Ordinance Laboratory where the shape memory property of the alloy was first discovered [18]. SMAs can be obtained in various shape and forms, either semi-finished products such as wires, ribbons, tubes and rods, or as finished form such helical springs and wire actuators at very reasonable prices [37].

SMP have a different behaviour than SMA when SME occurs. Upon activation SMP will lose all its mechanical strength and can return to their original shape. SMP devices have a lower mechanical strength than that made of SMA, as a result they can produce no significant force compared to that can be produced using SMA. Also, they have lower triggering temperature and much cheaper than SMA's and have a very large deformation value (300% higher than that of SMA) [12,28]. As a result, SMP can be used in manufacturing of active fasteners. SMP screws are a very common example of SMP fastening devices which can be used to hold various casings or assemblies together. Upon heating to its transition temperature, the screw threads straightens allowing the screws to fallout their location [28].

Generally, SMAs are suitable for AD applications requiring a displacement of a few millimetres or more and large forces for actuating device unlike SMPs AD applications. Also, if exposure to temperature is slow, AD effect can be slow [12].

3.3. Design of SMA actuator

SMA actuators are characterized by their integrated sensory and actuation functions that can sense any change in temperature and triggers by experiencing a shape change as a result of phase transformation. This eliminates the need for any external electronic sensors or control devices. This inherent actuation property of SMA allows it to operate in a clean, debris-less and spark free manner [38]. As a result, to enhance SMA actuating response, several factors must be considered such as composition of material, geometry of component, temperature of operation, conditions and rates of loading, thermomechanical history, conditions of processing and mostly combination of these parameters in many cases. It is important to understand the effect of all these factors on the overall mechanical response of SMA components [39].

Generally, overheating of the designed actuator must be prevented to ensure that the designed actuator can perform its function safely for a long period of time (about 10^6 cycles) before achieving its yield point and mechanical breakage [33]. Also, SMA exhibits a softening behaviour when actuator is cooled or heated under load (i.e. reduces the amount of recoverable strain). The recommended fatigue strength and strain of the material must not be reached (i.e. maximum load of 350 MPa, safe design load at 100 MPa and 3–4% strain); to increase lifetime of actuator [33].

To ensure a successful performance of SMA actuator, a systematic design process of actuator is essential. To satisfy these needs, this process should include specifying the market needs, capabilities of specific SMA materials and associated actuator designs. The elements of successful design process must include [37]:

1. Design requirements.
2. Design specifications.
3. Modelling and Prototype Development.
4. Testing and Evaluation.
5. Design Optimization.

Generally, design requirements include the power needed to activate SMA actuator, required force to be generated, needed recovery displacement and speed of recovery. While, design specifications describe all design details including SMA selected material, geometry and type of applied load.

3.4. Applications of active disassembly

Chiodo [12,29] invented AD at Brunel university by application of shape memory phenomena in the late 1990s for applications in several fields including manufacturing, aerospace, civil engineering and medicine. Since then smart materials proved that they can offer an excellent chance for reducing cost of automated disassembly design and optimized EOL scenarios [12,29]. Many efforts have been conducted to study the capability of AD implementation in any product, besides the economic and environmental impact of its implementation [27]. This is due to its inherent ability to provide a hierarchical, controlled and non-destructive specific component release from a product. AD technology has been introduced as a step change in the improvement of recycling process by increasing the quantity of precious materials that can be recovered [22].

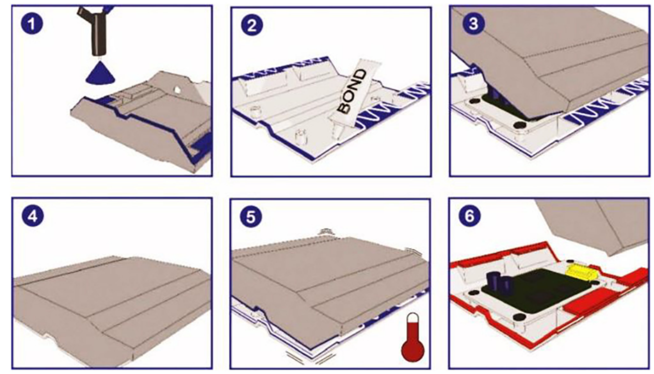

Fig. 3. The AD-IL assembly and disassembly process. 1. IL application; 2. bonding agent application (RTV: high temperature silicone sealant); 3. assembly; 4. use phase; 5. EOL AD treatment at Tx; 6. AD separation [27].

Chiodo [21] successfully applied and introduced AD to hundreds of products ranging from large automotive electronic products to handheld electronics. Electronic products such as LCDs, laptops and their subassemblies, cellular mobiles and other electronic components. Where SMA devices were manufactured and implemented inside the electronic device. Upon heating, the SME in the SMA is activated causing self-disassembly of housing or components within the electronic device [4]. Automotive components such as vehicle electronic control unit (ECU). ECU consists of a simple top and bottom covers enclosing a circuit board located at the mid distance between the two covers. The clean and easy separation of the covers can be facilitated by spraying an interstitial layer of smart material coating on one or more component to be bonded so that upon heating or vibration, the interstitial layer degrades allowing clean separation at EOL. Fig. 3, illustrates an explanation of this process [27].

Jones et al. [28,40], proposed several AD solutions that can promote safe disassembly of other automotive parts such as door glass and steering wheel airbag. Non-destructive dismantling of door window was conducted by replacing conventional glass retaining channel with another modified one having slots for SMA clips. These clips squeeze the rubber slip that grips the glass providing retention as illustrated in Fig. 4. Upon heating, the clips unrolls evenly allowing the glass to be freely pulled from its position. As for the steering wheel airbag, they can be removed safely by

Fig. 4. SMA clip grip the rubber and glass through a modified steel channel [28,40].

Please cite this article as: H. Abuzied, H. Senbel, M. Awad et al., A review of advances in design for disassembly with active disassembly applications, Engineering Science and Technology, an International Journal, https://doi.org/10.1016/j.jestch.2019.07.003

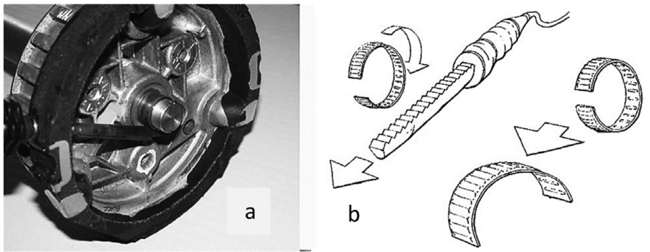

Fig. 5. a) A releasable steering wheel airbag mechanism where hot probe engages with the releasable bolt fixture on a cut away steering wheel hub. b) detailed illustration of Probe/SMA Collar interface [28].

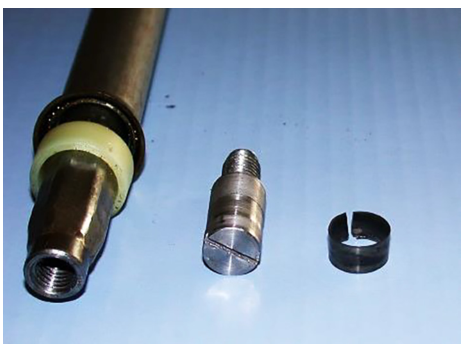

Fig. 6. Steering column, Modified bolt, SMA circlip [41].

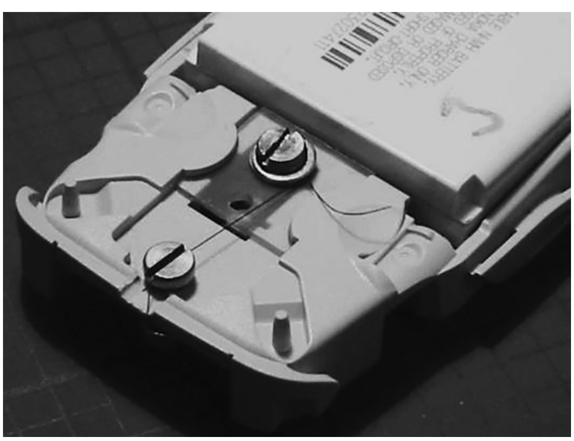

Fig. 7. Contraction of muscle wire pulls back the battery retaining tab allowing battery ejection (called latch mechanism) [42].

replacing the conventional bolt that holds the steering wheel with another modified bolt that have grooves cut in its shank to accept a flat large SMA circlip. So that, the steering wheel can be released by unrolling the circlip through heating the bolt as illustrated in Fig. 5 [28,40,41]. The individual components of steering wheel airbag releasing mechanism are shown in Fig. 6 [41].

For applications of AD in electronics sector, Jones et al. [42], proposed two mechanisms which promote self-powered disassembly of mobile phones batteries using muscle wire and residual power remaining in the battery at its EOL. This residual power is not enough to power the phone. Muscle wire is an SMA wire that contracts upon raising its temperature either by direct heating or by passage of an electric current through the wire as illustrated in Figs. 7 and 8.

Peeters et al. [43], demonstrated that that the economic profitability for AD can be increased by 27% higher than that of manual

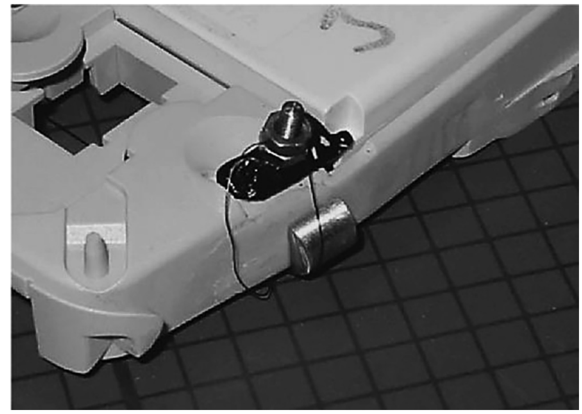

Fig. 8. Contraction of muscle wire pulls back the molded bell cranks in the battery housing allowing battery ejection (called active arm mechanism) [42].

disassembly, through implementation of snap fit active fasteners in payment terminals units (merchant units) that are used by seller to enter the payable amount. As for flat screen televisions such as LCDs and plasma display panels, implementation of active fasteners in their design stage increased greatly the value of recovered materials and recycling rate than that can be obtained using conventional EOL treatment [23]. Also, showed that the economic and environmental benefits of using AD are strongly product dependent, by implementation of active fasteners in eleven different electronic products having different material composition, product structures and lifetime distributions [44].

4. Discussion and conclusions

From the presented review it was shown that, the emerging need for a disassembly technique that allows an economic non-destructive separation of products at their EOL can be satisfied using AD. This is due to the capability of AD to support engineers in producing products that can undergo the disassembly process easily. Through, allowing a clean recovery of the initial components and reusable materials. As a result, AD has been promoted to be considered as a step forward for improving the treatment process of the products at their EOL, by allowing a self-non-destructive disassembly. Thus, disassembly can be promoted to be the most preferred EOL scenario of products.

The ability of AD to provide a generic fastening solution for diverse disassembly problems, encouraged it to be considered as a very interesting field for research. Also, it was shown that many efforts have been conducted to successfully apply AD in both electronic and automotive sectors. However, most of the conducted efforts for application of AD in these sectors were based on using SMA clips, SMA wires or SMA snap fits. All of these active fasteners are characterized by their ability to activate the disassembly process generating a small disassembly force and large displacement.

None of the efforts exerted was concerned with application of AD in products or large assemblies that requires a large disassembly force according to the authors' knowledge. As a result, the next phase of AD research can be focused on studying the economic viability of application of AD in products/large assemblies that require a large disassembly force. Specially, the disassembly of these assemblies/products could be a very difficult process using the conventional manual techniques. Consequently, their disassembly can be a very time-consuming process, due to the large effort that needs to be exerted by the labor. Furthermore, the usage of special tools might be needed which would require a special type of knowledge or experience from the labor.

Also, automatic techniques for the disassembly of these products/assemblies is not their preferred EOL scenario. This is due to the large investment costs required for the automatic process. Besides, the ability of the separated components or materials to be used in later generations of products cannot be guaranteed. Thus, more research for the economic viability of application of AD in products/large assemblies requiring large disassembly force can be considered as an emerging need and a very important field for research. In addition, studies to ensure that the recovered components and materials are not damaged from the disassembly of these products/assemblies are recommended to make sure that they can be reused again.

References

[1] F. Osti, A. Ceruti, A. Liverani, G. Caligiana, Semi-automatic design for disassembly strategy planning: an augmented reality approach, Procedia Manuf. 11 (2017) 1481–1488, https://doi.org/10.1016/j.promfg.2017.07.279.
[2] J.Y. Mule, Design for disassembly approaches on product development, Int. J. Sci. Eng. Res. 3 (2012) 1–5. http://www.ijser.org.
[3] T.F. Go, D.A. Wahab, M.N.A. Rahman, R. Ramli, A design framework for end-of-life vehicles recovery: optimization of disassembly sequence using genetic algorithms, Am. J. Environ. Sci. 6 (2010) 350–356. Department of Mechanical and Materials Engineering, Faculty of Engineering.
[4] J. Carrell, H.C. Zhang, D. Tate, H. Li, Review and Future of Active Disassembly, Int. J. Sustain. Eng. 2 (2009) 252–264, https://doi.org/10.1080/19397030903267431.
[5] S.L. Soh, S.K. Ong, A.Y.C. Nee, Application of design for disassembly from remanufacturing perspective, Procedia CIRP (2015) 577–582, https://doi.org/10.1016/j.procir.2014.07.028.
[6] Y.K. Yeşim Deniz Özkan Özen, Design for Disassembly in Smart Factories, in: Int. Symp. Prod. Res., Vienna, 2017
[7] S.L. Soh, S.K. Ong, A.Y.C. Nee, Design for assembly and disassembly for remanufacturing, Assem. Autom. 36 (2016) 12–24, https://doi.org/10.1108/AA-05-2015-040.
[8] C. Favi, M. Marconi, M. Germani, M. Mandolini, A design for disassembly tool oriented to mechatronic product de-manufacturing and recycling, Adv. Eng. Informatics. 39 (2019) 62–79, https://doi.org/10.1016/j.aei.2018.11.008.
[9] S.L. Soh, S.K. Ong, A.Y.C. Nee, Design for disassembly for remanufacturing: methodology and technology, Procedia CIRP. 15 (2014) 407–412, https://doi.org/10.1016/j.procir.2014.06.053.
[10] B. Willems, W. Dewulf, J. Duflou, Design for Active Disassembly (DfAD): an outline for future research, IEEE (2005) 129–134, https://doi.org/10.1109/ISEE.2005.1437007.
[11] J.R. Duflou, B. Willems, W. Dewulf, Towards self-disassembling products design solutions for economically feasible large-scale disassembly, Innov. Life Cycle Eng. Sustain. Dev. (2006) 87–110, https://doi.org/10.1007/1-4020-4617-0_6.
[12] J. Chiodo, N. Jones, Smart materials use in active disassembly, Assembly Automation 32 (2012) 8–24, https://doi.org/10.1108/01445151211198683.
[13] Ziout Aiman, "Innovative Design for Active Disassembly and Sustainable Product Recovery" (2013). Electronic Theses and Dissertations. Paper 4955.
[14] J. Oliveira, Z. Zeng, S. Berveiller, D. Bouscaud, F.M. Braz, R.M. Miranda, N. Zhou, J. Oliveira, Z. Zeng, S. Berveiller, D. Bouscaud, F.M.B. Fernandes, Laser Welding of Cu-Al-Be Shape Memory Alloys: Microstructure and Mechanical Properties, Materials and Design, Elsevier, 2018, pp. 145–152.
[15] J.P. Oliveira, R.M. Miranda, F.M. Braz Fernandes, Welding and joining of NiTi shape memory alloys, A Review, Prog. Mater. Sci. 88 (2017) 412–466, https://doi.org/10.1016/j.pmatsci.2017.04.008.
[16] Z. Liu, X. Li, H. Cheng, Y. Zhan, Research on mulit-multi-step active disassembly method of products based on ADSM, Post-Consumer Waste Recycling Opt. Prod. (2012).
[17] E. Parker, I. Sutherland, Stefano Carosio, Donato Zangani, Application of shape memory alloys to rock splitting: a successful example of co-operation between space research and industry, Proc. Conf. Acad. Ind. Coop. Sp. Res., Graz. (2000) 15–17, https://doi.org/10.15713/ins.mmj.3.
[18] Intrinsic Devices Inc., http://www.intrinsicdevices.com/Shape_Memory_Alloy_Fasteners.pdf, Web. (2017) 1–7.
[19] H.E. Karaca, E. Acar, H. Tobe, S.M. Saghaian, Nitihf-based shape memory alloys, Mater. Sci. Technol. 30 (2014) 1530–1544, https://doi.org/10.1179/1743284714y.0000000598.
[20] T. Maruyama, H. Kubo, Shape memory and superelastic alloys, technologies and applications, Woodhead Publishing limited (2011), https://doi.org/10.1533/9780857092625.2.141.
[21] Y. Li, K. Saitou, N. Kikuchi, S.J. Skerlos, P.Y. Papalambros, Design of heat-activated reversible integral attachments for product-embedded disassembly, in: Proc. – 2nd Int Symp. Environ. Conscious Des. Inverse Manuf., 2001, pp. 360–365, https://doi.org/10.1109/ECODIM.2001.992381.
[22] W.L. Ijomah, J.D. Chiodo, Application of active disassembly to extend profitable remanufacturing in small electrical and electronic products, Int. J. Sustain. Eng. 3 (2010) 246–257, https://doi.org/10.1080/19397038.2010.511298.
[23] W.D. Jef, R. Peeters, Paul Vanegas, Joost R. Duflou, Active disassembly for the end-of-life treatment of flat screen televisions: challenges and opportunities, in: Des. Innov. Value Towar. a Sustain. Soc. Proc. Eco Design 2011 7th Int. Symp. Environ. Conscious Des. Inverse Manuf., Springer Science+Business Media D Dordrecht, 2012, pp. 535–540.
[24] H.C. Zhang, J. Carrell, S. Wang, D. Tate, S. Imam, Investigation of a multiple trigger active disassembly element, CIRP Ann. – Manuf. Technol. 61 (2012) 27–30, https://doi.org/10.1016/j.cirp.2012.03.109.
[25] Z. Liu, Y. Zhan, H. Cheng, X. Li, S. Pan, Design method of active disassembly structure triggered by temperature-pressure coupling, Int. J. Precis. Eng. Manuf. 14 (2013) 1223–1228, https://doi.org/10.1007/s12541-013-0166-z.
[26] Y.R. Mathew, B.G. Babu, A real time experimental set up to analyse automatic actuation of a fire sprinkler using a shape memory alloy (Nitinol), Trans. FAMENA XXXIX. 3 (2015) 9–22.
[27] J.D. Chiodo, W.L. Ijomah, Use of active disassembly technology to improve remanufacturing productivity: automotive application, Int. J. Comput. Integr. Manuf. 27 (2014) 361–371, https://doi.org/10.1080/0951192X.2012.667151.
[28] N. Jones, D. Harrison, H. Hussein, E. Billett, J. Chiodo, Towards self-disassembling vehicles, J. Sustain. Prod. Des. 3 (2004) 59–74.
[29] L. Sun, W.M. Huang, H.B. Lu, C.C. Wang, J.L. Zhang, Shape memory technology for active assembly/disassembly: fundamentals, techniques and example applications, Assem. Autom. 34 (2014) 78–93, https://doi.org/10.1108/AA-03-2013-031.
[30] S. Faroughi, H. Haddad Khodaparast, M.I. Friswell, S.H. Hosseini, A shape memory alloy rod element based on the co-rotational formulation for nonlinear static analysis of tensegrity structures, J. Intell. Mater. Syst. Struct. 28 (2017) 35–46, https://doi.org/10.1177/1045389X16642532.
[31] O. Benafan, R.D. Noebe, T.J. Halsmer, Static rock splitters based on high temperature shape memory alloys for planetary explorations, Acta Astronaut. 118 (2016) 137–157, https://doi.org/10.1016/j.actaastro.2015.10.009.
[32] L. Miková, S. Medvecká, B.M. Kelemen, F. Trebuña, I. Virgala, Application of Shape Memory Alloy (SMA) as actuator, Metalurgija. 54 (2015) 169–172.
[33] J.M. Jani, M. Leary, A. Subic, M.A. Gibson, A review of shape memory alloy research, applications and opportunities, Mater. Des. J. 56 (2014) 1078–1113, https://doi.org/10.1016/J.MATDES.2013.11.084.
[34] M. Tabesh, J. Boyd, K.C. Atli, I. Karaman, D. Lagoudas, Design, fabrication, and testing of a multiple-actuation shape memory alloy pipe coupler, J. Intell. Mater. Syst. Struct. 29 (2017) 1165–1182, https://doi.org/10.1177/1045389X17730922.
[35] J.P. Oliveira, Z. Zeng, T. Omori, N. Zhou, R.M. Miranda, F.M.B. Fernandes, Improvement of damping properties in laser processed superelastic Cu-Al-Mn shape memory alloys, Mater. Des. 98 (2016) 280–284, https://doi.org/10.1016/j.matdes.2016.03.032.
[36] Y. Sutou, T. Omori, A. Furukawa, Y. Takahashi, R. Kainuma, K. Yamauchi, S. Yamashita, K. Ishida, Development of medical guide wire of Cu-Al-Mn-base superelastic alloy with functionally graded characteristics, J. Biomed. Mater. Res. – Part B Appl. Biomater. 69 (2004) 64–69, https://doi.org/10.1002/jbm.b.10079.
[37] Jaronie Mohd Jani, Martin Leary, Aleksandar Subic, Designing shape memory alloy linear actuators: a review, J. Intell. Mater. Syst. Struct. 28 (13) (2017) 1699–1718, https://doi.org/10.1177/1045389X16679296.
[38] Van Nostrand's Scientific Encyclopedia, Shape-memory Alloys, (2006) 1–15, John wiley & Sons, Inc.
[39] A.R. Srinivasa, A. Rao, J.N. Reddy, Design of Shape Memory Alloy (SMA) Actuators, SPRINGER B, Springer Briefs in Applied sciences and Technology· Computational Mechanics, 2015.
[40] N. Jones, D. Harrison, J. Chiodo, E. Billett, Design for Automotive Glass Removal Using Active Disassembly, in: Proc. 2002 SAE Int. Body Eng. Conf. Exhib. Automot. Transp. Technol. Conf., 2002, https://doi.org/10.4271/2002-01-2246.
[41] N. Jones, D. Harrison, J. Chiodo, E. Billett, Safe Steering Wheel Airbag Removal Using Active Disassembly, (2002) 655–660.
[42] N. Jones, D. Harrison, H. Hussein, E. Billett, J. Chiodo, Electrically self-powered active disassembly, Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 218 (2004) 689–697, https://doi.org/10.1177/095440540421800702.
[43] J.R. Peeters, P. Vanegas, W. Dewulf, J.R. Duflou, Economic and environmental evaluation of fasteners for active disassembly: a case study for payment terminals, Procedia CIRP. 29 (2015) 704–709, https://doi.org/10.1016/j.procir.2015.01.031.
[44] J.R. Peeters, P. Vanegas, W. Dewulf, J.R. Duflou, Economic and environmental evaluation of design for active disassembly, J. Cleaner Prod. 140 (2017) 1182–1193, https://doi.org/10.1016/j.jclepro.2016.10.043.

Please cite this article as: H. Abuzied, H. Senbel, M. Awad et al., A review of advances in design for disassembly with active disassembly applications, Engineering Science and Technology, an International Journal, https://doi.org/10.1016/j.jestch.2019.07.003