Biomimetic design for remanufacture in the context of design for assembly

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Abstract: In this paper, a biomimetic design method is applied to a specific problem in design for remanufacture. First summarized is remanufacture as an option to disposal at product end of life, and how products may be designed for ease of remanufacture. Next identified is a contradiction between a design-for-remanufacture strategy and design-for-assembly preferences. Specifically, making failure-prone features into separate parts facilitates remanufacture but results in additional parts to assemble. An example involving snap fits as a method of fastening and joining is used to illustrate the contradiction. To obtain ideas on how to address this contradiction, a biomimetic search method was used to find biological phenomena that are analogous to remanufacture. One such phenomenon is described and used to develop a concept that satisfies both design-for-remanufacture and design-for-assembly preferences.

Keywords: biomimetic design, remanufacture, design for assembly

1 BACKGROUND FOR REMANUFACTURE

1.1 Remanufacture and other product end-of-life options

Product design for end of life is prompted by existing and anticipated legislation that assigns to manufacturers the responsibility for their products at the end of life. Alternatives to landfill or incineration include recycling for scrap material, remanufacture and maintenance. Maintenance extends product life through individual upkeep or repair of specific failures. Remanufacture is a production-batch process of disassembly, cleaning, refurbishment and replacement of parts in worn, defective or obsolete products. Scrap-material recycling involves separating a product into its constituent materials and reprocessing the materials.

1.2 Benefits of remanufacture

Remanufacturing is recycling at the parts level as opposed to the scrap-material level. Recycling at the higher level of components avoids resource consumption for possibly unnecessary reprocessing of material while preserving the value-added nature of components. Remanufacturing also postpones the eventual degradation of the raw material through contamination and molecular breakdown, which is frequently characteristic of scrap-material recycling. In addition, remanufacture can divert parts made from unrecyclable materials from landfill. The production-batch nature of the remanufacturing process enables it to salvage functionally failed but repairable products that are discarded due to high labour costs associated with individual repair.

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1.3 Design to facilitate remanufacture

While product design that facilitates any of the steps involved in remanufacture, namely disassembly, sorting, cleaning, refurbishment, reassembly and testing, will facilitate remanufacture, the essential goal in remanufacture is part reuse. If a part cannot be reused as is or after refurbishment, the ease of disassembly, cleaning or reassembly will not matter.

Examples of part refurbishment include application of mechanical force to reverse plastic deformation such as warps and creases, closing and filling cracks through mechanical pressure or welding, and rebuilding worn surfaces using metal spraying and welding. These refurbishment processes can be labour and equipment intensive. Also, refurbishment processes that further consume a part, such as reboring a worn cylinder to fit an oversized piston, can be performed only a limited number of times. The reliability of a reworked part may also be compromised.

Literature on automotive remanufacturing and collaboration with remanufacturers of photocopiers, toner cartridges and automotive after-market products revealed a strong preference for failure and wear to be isolated in as small a part as possible. For example, cylinder sleeves can be replaced, enabling the bulk of the part to be reused without rework. Unfortunately, making separable parts that are prone to wear directly counters the part-consolidation tenet of design for assembly. In addition, separate parts that introduce different materials are not favoured by design for recycling. Design for assembly and design for recycling are both more widely practised than design for remanufacture. Therefore design for remanufacture ought to be considered in the context of assembly, as well as other end-of-life options.

The processes of disassembly and reassembly are particularly relevant to product end-of-life options and are clearly affected by the choice in fastening and joining method. An example will be presented that concerns product fastening and joining, following a summary of related work in design for disassembly as it applies to product end of life.

2 RELATED WORK

Since disassembly is a necessary and critical process for the end-of-life options previously identified, there has been significant research on how to design products for easier disassembly. Much of this research emphasizes disassembly to facilitate recycling. The goal of disassembly for recycling is to separate different materials to the greatest extent with the least effort. Joints between parts of the same material need not be separated if the joining element is recycling compatible with the part material. Disassembly that damages the part is frequently acceptable as long as cross-contamination of materials does not result. Other work extends to inclusion of disassembly for maintenance as well as remanufacture. The primary emphasis in disassembly to facilitate maintenance is to minimize machine downtime and maintenance labour cost.

Although design that facilitates disassembly for maintenance and recycling can frequently benefit remanufacture, it does not encompass disassembly to facilitate remanufacture. Remanufacture often requires disassembly of joints that are not accessed for routine maintenance tasks. The labour rate for remanufacture is typically lower than for field maintenance. Also, the urgency of returning equipment to operation is not as great in remanufacture as it can be for maintenance. While speed of access is important in remanufacture, unplanned and unrepairable damage to the part as a result of disassembly or reassembly prevents part reuse.

Difficulties in disassembly for service and recycling have been distilled into design guidelines that include which fastening methods are preferred. These guidelines are presented as applicable to product design for remanufacture as well as recycling and maintenance. Guidelines and examples that promote the use of snap fits abound. 'Do not use inserts' rules are also ubiquitous. While these rules are based on valid difficulties in disassembly, problems due to parts rendered unusable as a result of disassembly were not emphasized.

Previous work by the present author and a co-author [**1**, **2**] applied a cost model that considered the total cost determined by the choice of fastening and joining method as the sum of the initial manufacturing and assembly cost, the cost of disassembly and reassembly required for maintenance and remanufacture, including the cost of replacement of parts damaged during disassembly, and the cost of final disassembly for recyling. This cost model was applied to case studies in the remanufacture of photocopiers and toner cartridges.

The case studies confirmed that the probability and consequence of damage to parts during disassembly and reassembly imposed by the fastening or joining method can significantly affect remanufacture cost. On the other hand, disassembly methods destructive to the fastener that do not damage the fastened parts, such as drilling out and replacing a rivet, are acceptable in remanufacture.

In one case study, the stripping of internal threads preventable by threaded inserts resulted in parts that were not reused. Although inserts may increase costs during first manufacture and assembly, as well as recycling, inserts allow the reuse of parts that would otherwise be disposed of during remanufacture. As part cost increases, the extra effort required to install inserts will probably pay off, particularly if the product will undergo several remanufacture cycles.

Another case study showed that, while snap fits may be desirable for first manufacture and assembly, as well as recycling, snap fits that tend to fail are costly for remanufacture. Since snap-fit features on components are difficult to repair, their failure typically results in the discard rather than reuse of the components [**3**]. The example of snap fits will be continued in this paper.

3 SNAP FITS CONTINUED

Figures 1 and 2 show snap-fit features that failed during the remanufacture of toner cartridges. While snap fits are desirable because they allow for fast assembly and possibly disassembly and reassembly without introducing a different part or material, the integration of snap-fit features into parts makes their failure more costly than the failure of separate removable fastening features. However, as mentioned earlier, making failure-prone parts separate directly contradicts the part-consolidation tenet of design for assembly. The next section aims to use biomimetic design to develop concepts to address this contradiction.

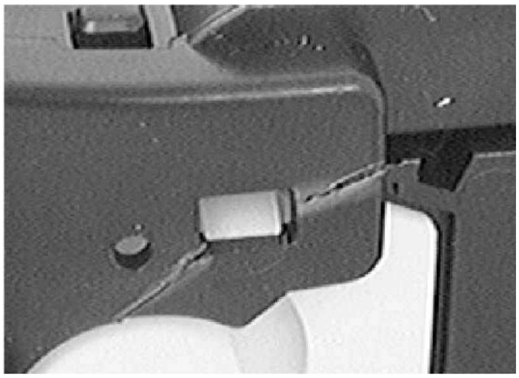

Fig. 1 Damaged snap-fit fastener. (From reference [**2**])

4 BIOMIMETIC DESIGN

Many examples of biomimetic design exist, but not yet available is an objective systematic method of finding relevant biological phenomena for any given engineering problem. Recent work by the present author has sought to develop such a method [**5**, **6**]. Described below is one of several analogies relevant to remanufacture found using this method, and how strategies are extracted from this analogy and subsequently implemented for the snap-fit problem.

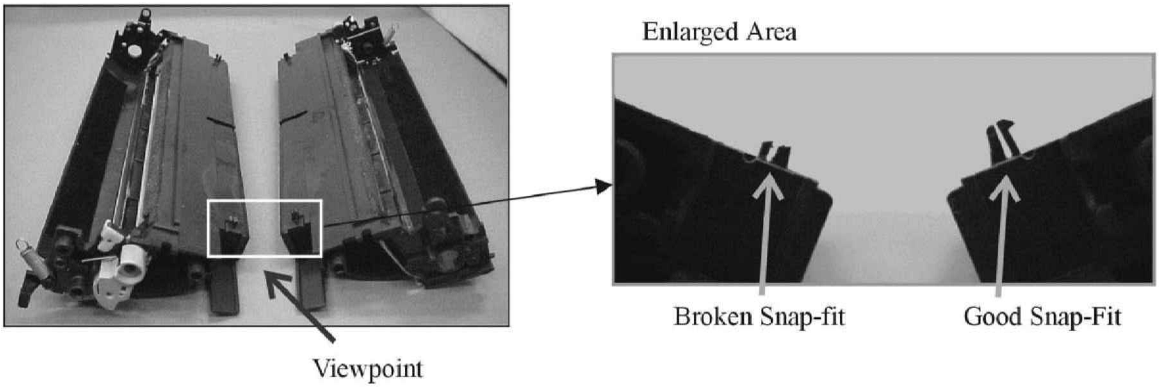

Fig. 2 Damaged snap-fit fastener. (From reference [**4**])

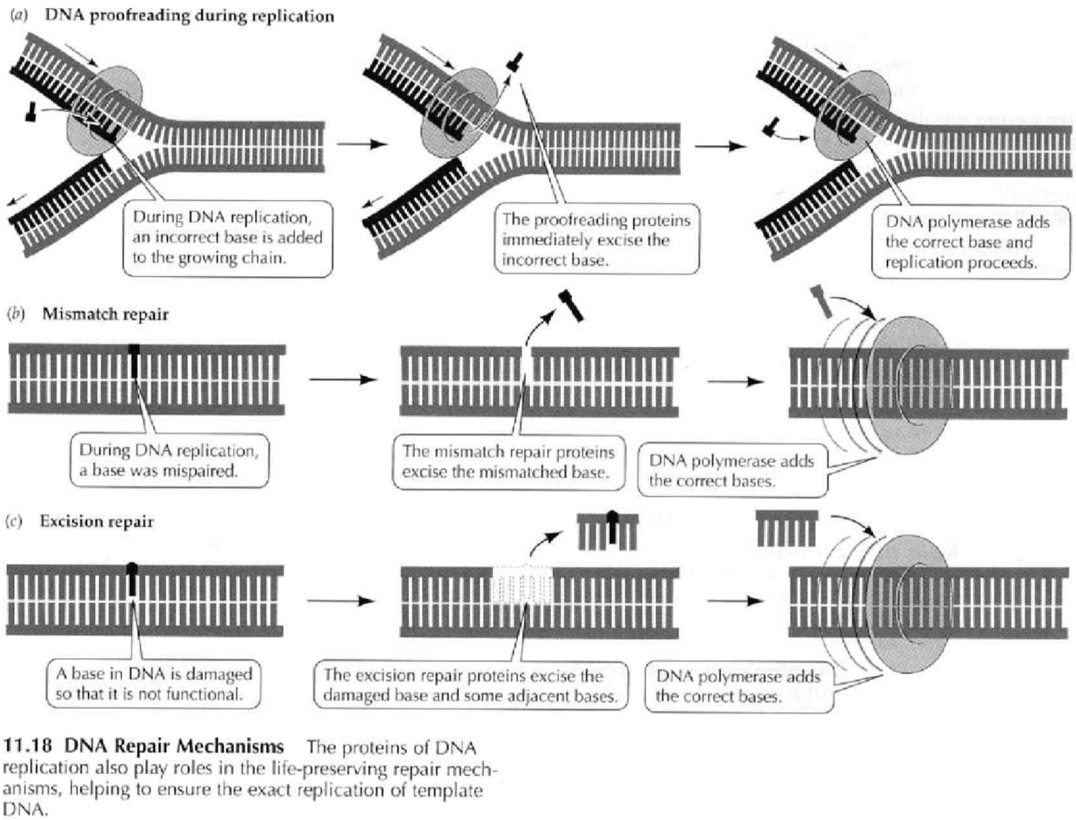

Fig. 3 DNA repair mechanisms. (From reference [**7**]. Reproduced by permission)

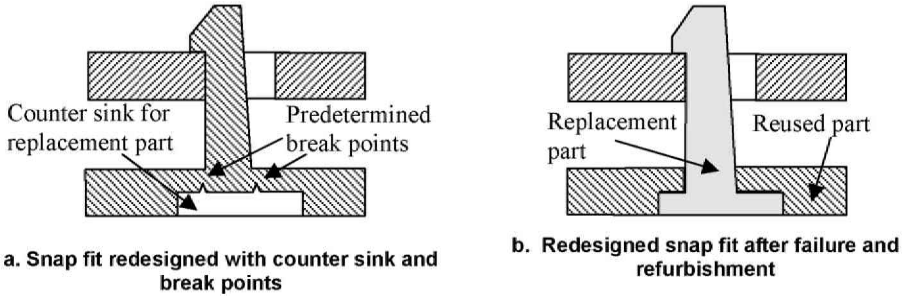

Fig. 4 Break points in snap fit to facilitate repair [**5**]

4.1 Deoxyribonucleic acid repair mechanisms

The first phenomenon of interest concerns deoxyribonucleic acid (DNA) repair processes. Figure 3 (from reference [**7**]) shows three types of DNA repair mechanisms: DNA proofreading during replication, mismatch repair and excision repair. Both the proofreading and mismatch repairs described refer to corrections of errors in assembly, i.e. an undamaged but incorrect base in a particular position. Excision repair targets damaged sections of a DNA molecule, including that which occurs during the life of the cell. This correlates more closely with damage that occurs to a product during its useful life and is a more useful analogy for remanufacture.

During excision repair, several specific proteins find, cut away and replace the defective and adjacent bases. Friedberg *et al*. [**8**] indicated that one protein 'induces a conformational change' in the DNA such that another protein can perform the appropriate excision.

The strategy taken from the above analogy is that a conformational change is induced to facilitate separation of a defective region. Similarly, predetermined failure-induced deformation in a product can facilitate replacement of the defective region. Thus the failure-prone region is not necessarily a separate part during original manufacture but could be structured such that failure causes self-disassembly. For example, a wear-prone part could be designed such that the gradual thinning of a surface causes that surface to break away from the rest of the part. Applied to snap fits, the break points shown in Fig. 4 encourage breakage to occur in a predetermined manner, facilitating the reuse of such parts.

5 SUMMARY

An example involving snap fits is used to illustrate how fastening and joining that facilitate assembly and recycling could impede remanufacturing. This and other examples suggest that elements of fastening methods that are prone to failure be made separable from the remainder of the part. However, this conclusion directly contradicts the part-consolidation tenet of design for assembly. A biological analogy was used to develop a concept that facilitates remanufacture, while considering assembly preferences.

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