ISOLATING LCD'S AT END-OF-LIFE USING ACTIVE DISASSEMBLY TECHNOLOGY: A FEASIBILITY STUDY

J.D. Chiodo, J. McLaren, E.H. Billett and D.J. Harrison

Cleaner Electronics Research, Brunel University, Egham, Surrey, TW20 0JZ, UK
Joseph.Chiodo@brunel.ac.uk,
http://www.brunel.ac.uk/~dtsrjdc/ADSM.html

Abstract - The European Union draft Waste Electrical and Electronic Equipment (WEEE) Directive calls for the removal and separate treatment of Liquid Crystal Displays (LCD). This aspect of the legislation will potentially have an important impact upon the future 'End of Life' (EoL) processing of much WEEE.

Active Disassembly using Smart Materials (ADSM) has been proven to have potential applicability in self-dismantling, non-destructive and rapid disassembly of small electronic products. This paper investigates the technical feasibility of removing LCD screens from IT communication products using ASDM technology. In this paper an option is suggested to cleanly separate LCD screens from printed circuit boards, utilizing an LCD bracket made from 'Shape Memory Polymer'. The case study products employed are Nokia Japanese J-Phones. Demonstration experiments with initial results are presented, and future developments discussed. SMP glass transformation temperatures (Tg) and time efficiency in disassembly are considered.

I. INTRODUCTION

A. End-of-Life Treatment of Liquid Crystal Displays

A variety of Liquid Crystal Displays are found in consumer electronics, common types include; Twisted and Super Twisted Nematic Liquid Crystal Displays, and Active Matrix Displays. The typical composition of LCDs are; glass, liquid crystals, pigments, resins, Indium Tin Oxides; and in active matrix displays metals such as tantalum, titanium, chromium, aluminium, copper and molybdenum [1].

There are almost 400 different types of Liquid Crystal compounds use in displays. Generally these are polycyclic aromatic hydrocarbons, or halogenated aromatic hydocarbons. [2]. Modern performance requirements have led to the development of complex blends of crystal mixtures each compound manufactured using sophisticated production processes.

Little environmental data is openly available about the use of liquid crystals, which causes difficulty in assessing their potential environmental impact [1,2,3]. Producers of LCD screens and industry groups have stated that Liquid Crystals do not contain hazardous materials, and should not be classified as hazardous waste (e.g. EIAJ reference [4] page 1, and MEREC tests reference [1] page E35/36). However the European Commission is not of this opinion and thus has applied the precautionary principal to the current draft WEEE directive stating that all LCD components must be removed at 'End-of-Life' (EoL) and treated separately [5]. The requirements for treatment of separated LCDs will be subject to the classification of waste as defined by the environmental agencies of the EU member state countries.

Only one EoL process is known to have been specifically developed for LCDs by the VICTOR Company of Berlin. This process involves rough shredding of the displays followed by separation of liquid crystal from other materials and finally, elimination of crystals by catalytic decomposition (for further details see Valortube Commission. 1999). However, it is likely that unless waste handlers can categorically state that the nature of specific waste LCDs is not defined as Special Waste, that LCDs will be required to be treated as Special Waste and stored in underground dumps. This EoL route is costly. Furthermore, if the LCD fraction of the product can not be separated from the product, then it is likely that the entire product will have to be disposed of in this manner, at additional cost [6].

0-7803-5962-3/00/$10.00 ©2000 IEEE

These issues highlight the need to develop efficient and cost effective methods for product disassembly and automatic, non-destructive methods for LCD isolation. The ADSM prototypes described in previous papers [7,8,9,10,11] suggest that ADSM may be a potential route to separation of product casings to reveal the printed circuit boards. The aim of this paper is to develop ADSM component prototypes to isolate the LCDs from printed circuit boards.

B The ADSM End of Life Scenario

Future trends in product design engineering point towards recycling as an integral part of the life cycle of electronic consumer products. Automating the dismantling of post consumer product is still seen as a product specific endeavour. Unlike other forms of disassembly, ADSM would enable an industry wide or generic approach to a non-destructive dismantling process, increasing the ability to separate toxic and dissimilar components and materials. Past ADSM research has been conducted on a wide variety of WEEE goods with the majority concentrating on small handheld products [7,8,9,10,11].

C. Prior SMP Device Developments

Earlier work consisted of creating new 'Shape Memory Polymer' (SMP) [12] fasteners with particularly unique properties; Table 1. SMP 'Mechanical Property Loss' (MPL) screws were first developed and manufactured; Figure 1. Further developments were made with 'Shape Memory Effect' (SME) SMP screws whereby at 'Glass Transition Temperature' (Tg) [13], the threads receded into the shaft of the screw bolt; Figure 2 [9]. These newer SMP devices capitalized on metamorphic [14] and SME properties; Figure 3. Preliminary investigation of these two screw designs suggested that they would enable effective disassembly when incorporated into the candidate mobile phones [8,9].

II. METHOD

In this investigation, the feasibility of using ADSM technology for isolating LCD screens from their host printed wiring board mounting brackets has been explored. Finnish made Nokia Japanese J-Phones have been used as demonstration products. In these products, the LCDs are mounted onto the printed circuit using a polycarbonate bracket, which is assembled onto the board using integral moulded clip fixings. The LCD joins the bracket on the opposite surface, again using integral clip fixings. A speaker, switch and rubber mount are also housed using push-fit assembly within the LCD bracket.

Firstly, novel SMP LCD brackets were developed to replace the original polycarbonate LCD bracket. These SMP brackets were moulded from the original mobile phones' polycarbonate brackets; Figure 4. These components were specifically developed and manufactured for this ongoing project, and will be referred to as SMP brackets. Secondly, the LCD was remounted onto the circuit board using the new SMP bracket, and tests were conducted to trigger the disassembly of the components; thereby demonstrating the isolation of LCD screens from their host printed circuit boards.

A. Development of Novel SMP LCD Brackets.

A Two-part potting compound (SMP 4510) was used for the creation of the new SMP LCD releasable brackets; Table 1. A silicone mould of the original polycarbonate brackets was made. The mould of the new bracket must be in the shape which *aids* active disassembly. Thus a series of steps were taken to develop the SMP LCD brackets:

1. The original LCD bracket was removed from the mobile phone and exposed to higher temperature (100°-120°C) to manipulate it to the desired shape required for the eventual SMP bracket; Figure 4. This will be the final shape that releases the LCD from its host bracket and the bracket's host PCB.
2. Once the polycarbonate LCD bracket was deformed to shape and cooled, it was used to create the silicone mould cavity. Two Part potting compound 4510 SMP was then injection moulded into the silicone mould cavity to manufacture a bowed SMP bracket.
3. With this now 'final' bowed shape SMP LCD bracket manufactured, it is ready for further manipulation. The SMP bracket is exposed to above its 45°C Tg; at least 53.5°C for its upper limit; Table 1. The form is now manipulated back to the manufacturer's original specifications; Figures 6 and 7. In this case, it means bending the form flat from the moulded bowed form; Figure 4. The entire device is then immersed in a cold bath (5°C), well below Tg for shape configuration, also known as 'shape fixity' [15]. Cold bath immersion re-aligns the molecular structure of the SMP to its fixed container or in this case, the secondary mould of an unbowed SMP bracket; Figure 7.
4. Finally the full subassembly is reassembled onto the printed wiring board with the SMP LCD bracket holding the LCD screen, diffuser sheet, speaker, switch and rubber mounts in place. The subassembly is now ready for experimentation; Figure 7.

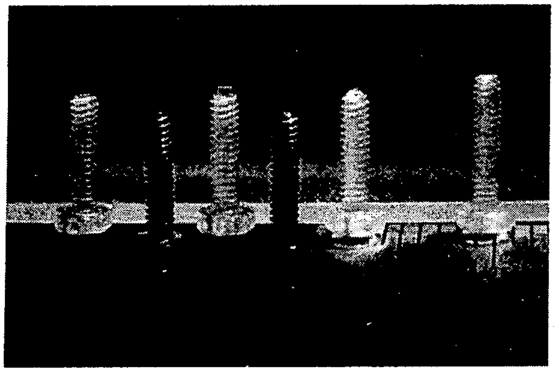


Figure 1. First developed SMP MPL Releasable Fastener Screws (M1x7.0mm) tested on various mobile phones. Mean disassembly time; ≈ 20 sec.

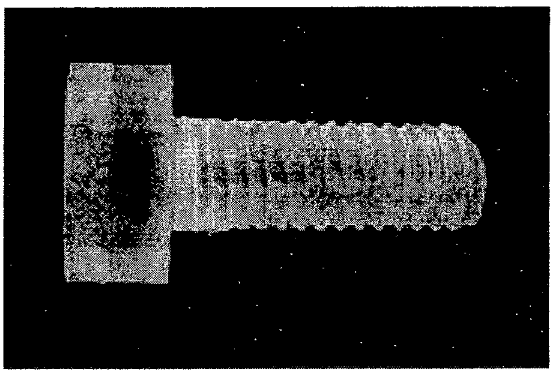


Figure 2. Later developed SMP Screws (M4x10.0mm). The thread-less shaft was post formed in its secondary mould. Also tested on the various stated mobile phones. Mean disassembly time was ≈ 8 seconds. Best-achieved disassembly time; 1.5 sec.

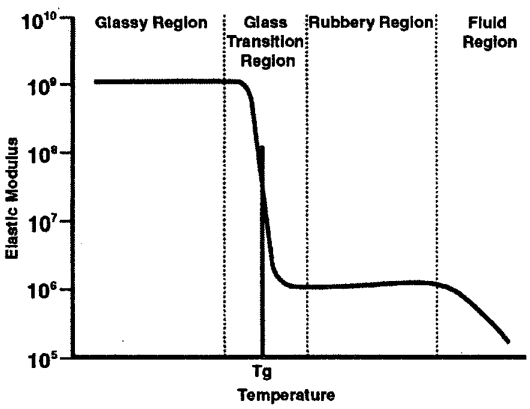


Figure 3. Elastic Modulus – Temperature / Tg [6].

TABLE 1.
Shape Memory Polymer Properties.

General Shape Memory Polymer Properties		
Glass Transition (Tg)	**(°C)**	**End Tg (°C)**
Standard (2510)	25	31.5 - 33.5
Standard (3510)	35	41.5 - 43.5
Standard (4510)	45	51.5 - 53.5
Standard (5510)	55	61.5 - 63.5
Optional (7510)	70	76.5 - 78.5
Laboratory samples	<120	t.b.a.
Transformation Bandwidth	14 (+-7°)	-
Typical Mechanical Properties (for SMP <=55°C)		
Hardness	Tg -20 Tg +20	75 Shore D 25 Shore D
Tensile Strength	Tg -20 Tg +20	60 MPa 30 MPa
Elongation	Tg +20	> 600%
Bending Modulus	Tg +20	80 MPa
Thermal, Electrical and Optical Properties		
Thermal conductivity	Tg -20 Tg +20	.35 W/m/°C .58 W/m/°C
Coefficient of Thermal Expansion	Tg -20 Tg +20	2.75x10-5/°C 21.7x10-5/°C
Dielectric Constant	Tg -20 Tg +20	3.47 4.13
Index of Refraction	Tg -20 Tg +20	1.557 1.543
Physical and Chemical Properties		
After Processing	Optically Clear	
Specific Weight	1.2	
Melting point	190°C	
Chemical Resistance to:		
Acids	Excellent	
Bases	Excellent	
Inorganic Solvents	Fair	
Thermal Cycling	Excellent (>1000s)	
Weatherability	Excellent	
Hydrolysis	Excellent	
Water Absorption	0.7% by Weight	

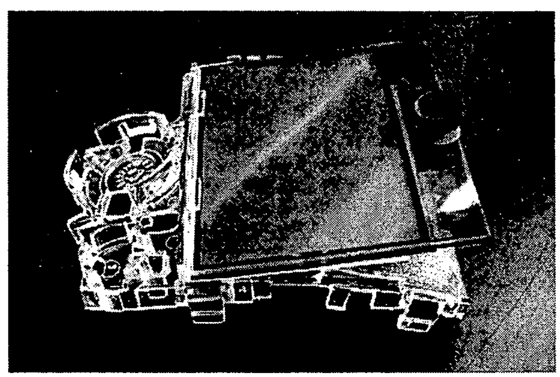


Figure 4. Manipulated polycarbonate LCD bracket used for the SMP bracket-moulding cavity. The position of the LCD screen indicates intended SMP bracket configuration after 'Shape Memory Effect' (SME) transformation.

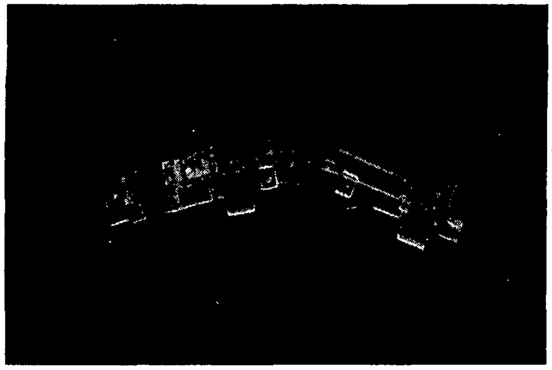


Figure 5. Novel SMP component in initial moulded configuration, prior to <Tg manipulation It will return to this 'shape' after SME transformation, allowing the LCD to release without destruction.

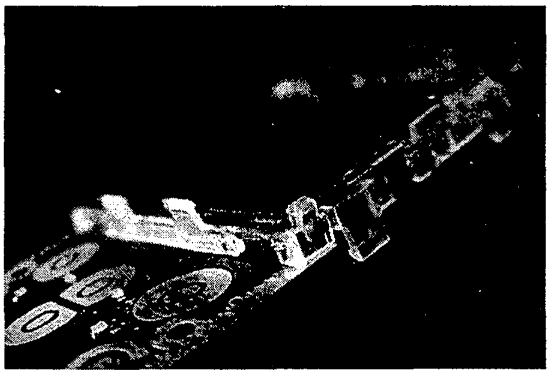


Figure 6, SMP bracket in its secondary configuration for the use phase prior to Tg exposure. Once exposed to its Tg, the bracket deforms to self eject the LCD without destruction.

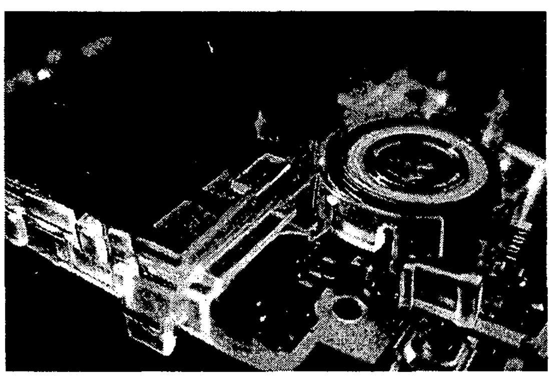


Figure 7. SMP LCD bracket placing other components; speaker, switch and rubber positioning posts. This bracket is identical to the dimensional specifications of the original polycarbonate bracket.

B. Testing of the SMP Brackets

Having re-assembled the LCD screen back onto the printed circuit board using the novel SMP bracket, the assembly is ready for testing. Experiment trials were conducted using heat transfer via total hot water immersion; Figure 7. Other potential methods of heat transfer such as convection or infrared have been previously discussed in [8,9]. The ADSM bracket subassemblies were activated at an exposure temperature of 85.6°C ±1.5°C. The tests were conducted from three storage temperature zones of +22.8°C (±0.9°), +5.1°C (±1.1) and -23.3°C (±2.9). The storage temperature sets were in three diverse temperature settings to indicate likely performance of the components in the use phase. Thirty tests in each zone were conducted for statistical robustness.

Although the Tg of the SMP used in the manufacture of these SMP (LCD) brackets is only 45°C; an easily achievable ambient temperature during product use; this was decided on the basis of availability and cost for initial experimentation. Future work will specify higher Tg SMP. Ideal Tg triggering would take place at 85°C or higher in order to accommodate manufacturer's performance requirements.

Exposure of the assembly to temperatures above Tg, activates the SMP bracket to revert it back to the original moulded shape, as in Step 1 of Part II, A, *(Development of Novel SMP LCD Brackets)*. At this point, the LCD is self ejected non-destructively from the host SMP bracket and the bracket also unclips it's self from the printed wiring board. The activation also separates the speaker, switch and rubber mounts from the bracket; Figures 8 and 9.

Within the above sequence, one complete active disassembly operation is successfully completed. The properties of the SMP allow the change of state to be repeated a number of times, provided the SMP device is kept within its 600% elongation while above Tg. This may potentially facilitate multiple closed loop re-use of this component; Figure 10. However, the SMP bracket must firstly be reconfigured for the subsequent re-use. This may be done by one of two ways; firstly, by keeping the SMP bracket above Tg, its elastic modulus is drastically lower than below Tg (to the order of approximately 1%); Figure 3, at this point it is soft enough to accept re-configuration by secondary moulding. The second way is to allow below Tg exposure to the LCD bracket, while then later exposing it to above its Tg for the same re-configuration procedure. This can be considered a unique form of remanufacture. Notice the bowed form is visibly identical to the original manufactured form before and after the ADSM process; Figures 5 and 8. Figure 10 indicates the 'remanufacture' of the SMP LCD bracket while, Figure 9 indicates the 'activation' during ADSM.

Figure 8. Successful active disassembly tests for clean LCD isolation with the SMP LCD bracket cleanly self-ejecting the LCD, speaker, switch and placement components within the bracket.

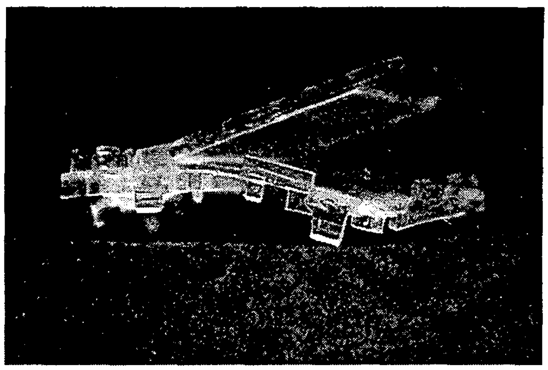


Figure 9. Post ADSM, before LCD bracket re-configuration. The LCD is in place to indicate the active disassembly procedure of self-separation.

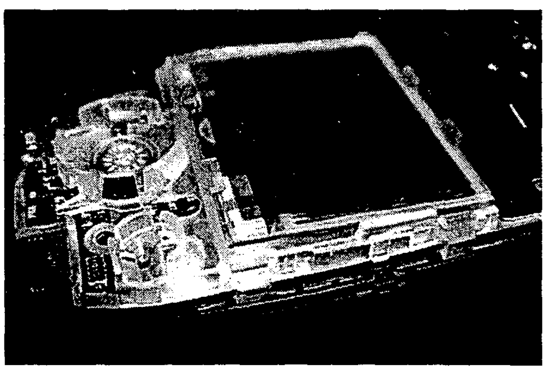


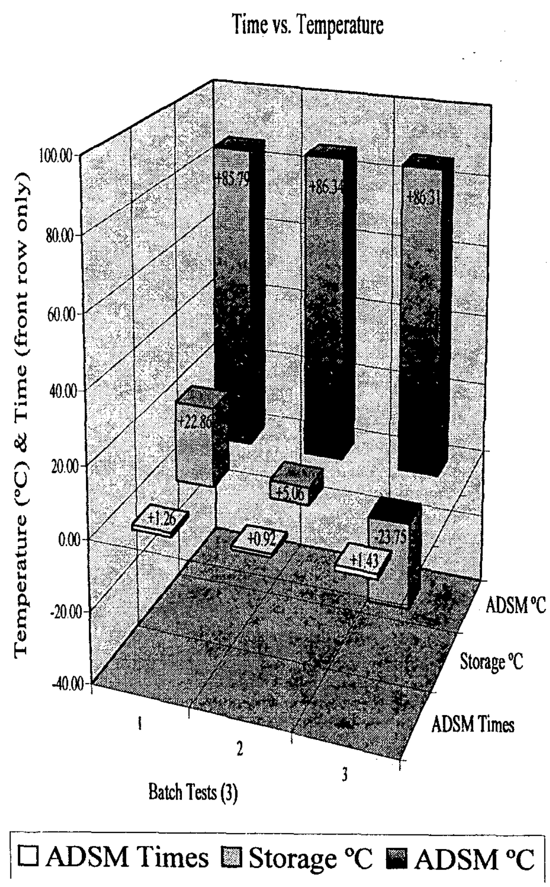
Figure 10. Post re-configuration of the SMP LCD bracket allows for 're-manufacture' of the device's host product. SMP, kept within its 600% elongation while above Tg, retains a high cycle value for re-configuration.

III. RESULTS

The mechanical properties of SMP enabled active disassembly of the LCD and its bracket by providing a sharp drop in elastic modulus by the 45°C Tg.

In addition to the SME properties of the SMP, mechanical property loss aspects of the SMP's Tg exposure aided in the very quick disassembly and self-ejection of the LCD from its host SMP bracket. The results in Table 2 show that the disassembly times range from an average of 0.9sec. to 1.43sec. depending upon the original storage temperature. The LCD screen, speaker and switch, are all effectively loosened by transformation of the SMP LCD bracket, such that they fall apart separately when turned upside down.

TABLE 2.
Storage to Immersion ADSM.



Sets:	1	2	3
ADSM Times	1.26	0.92	1.43
Storage °C	22.86	5.06	-23.75
ADSM °C	85.79	86.34	86.31

IV. CONCLUSIONS AND DISCUSSION

The isolation of LCD screens is a likely requirement of the forthcoming EU WEEE legislation, that industry anticipates will cause significant technical difficulty to achieve.

Previous work has demonstrated the effective disassembly of product casings from internal components. However, until now the use of smart materials has not been used to disassemble and isolate individual internal components. The development of releasable LCD brackets made of shape memory polymer is novel, and the results of these initial tests demonstrate a promising method for separation of the LCDs from the printed circuit board. Another more radical approach to achieving the same result might involve re-design of the outer product mouldings and internal screen connectors to incorporate novel LCD 'modules' which could potentially be separated from the product without any prior product disassembly.

Additional findings from the experiments reported in this paper indicate that SMP brackets are able to return to their originally moulded shape after shape memory transformation. This demonstrates the reversible shape memory effect associated with this smart material.

Lastly, while the experiments reported in this paper do *not* demonstrate the combination of disassembly of product outer casings simultaneously with the separation of the Liquid Crystal Display, this will be investigated in future work. However, at this stage there is no reason to suggest that both ADSM techniques will not be able to perform simultaneously effectively. Further we believe that the two techniques could also be deployed such as to stager product disassembly in separate stages using different Tg actuation temperatures. Thus, a range of potential techniques may be possible deployed to the advantage of differing EoL processing requirements.

ACKNOWLEDGMENT

The work has been funded by the EPSRC, Design for Whole Life Cycle Programme. Thanks to; Richard Morris for his tremendous help in the digital and video work; Dr. Shunichi Hayashi from Mitsubishi Heavy Industries, Nagoya Japan for his generous SMP technical expertise and SMP samples, and Pia Tanskanen at Nokia Research Center, Helsinki for case study products.

REFERENCES

[1] Valortube Commission. 1999. "Final Report of the Flat Panel Displays Committee (June 1997 / December 1998)" Flat Panel Displays Committee of the Valortube Commission. An initiative of ADEME (French Agency for the Environment and Energy Management) and FIEEC (French Federation of the Electrical and Electronics Industries).

[2] MCC (Microelectronics and Computer Technology Corporation) 1998(?). "Computer Display Industry and Technology Profile" Report produced under co-operative agreement with US EPA Design for the Environment Branch.

[3] Orango AB and Atlantic Consulting. 1999. "EU Eco-Label for Portable Computers – Suggested Criteria. Version 1.05"

[4] LIREC (LCD Industries Research Committee) 1999. "Appropriate treatment of Waste LCDs" Report of the Electronic Industries Association of Japan (EIAJ)

[5] EU (European Union) DGXI 1999. "3rd Draft Proposal for Directive on Waste Electrical and Electronic Equipment. 76/769/EEC"

[6] Ram B., *et al.*, 1999 'Environmental Performance of Mobile Products' Proceedings of IEEE Int'l Symposium on Electronics and the Environment, pp. 140 - 145. ISBN 0-7803-5495-8.

[7] Chiodo, J. D., *et al.*, Active Disassembly, Journal of Sustainable Design, October, 1998. ISSN 1367-6679

[8] Chiodo, J. D., *et al.*, 'Preliminary Investigations of Active Disassembly Using Shape Memory Polymers: EcoDesign'99: First International Symposium on Environmentally Conscious Design and Inverse Manufacturing', IEEE, (Tokyo, Japan, 1 - 3 Feb 1999), pp. 590 - 596. ISBN 0-7695-0007-2.

[9] Chiodo, J. D., *et al.*, 'Active Disassembly Using Shape Memory Polymers for the Mobile Industry: 1999 IEEE Int'l Symposium on Electronics and the Environment - ISEE - 1999' (Danvers, Massachusetts, 11 - 13 May 1999), pp. 151 - 156. ISBN 0-7803-5495-8.

[10] Chiodo, J. D., *et al.*, 'Shape Memory Alloy Actuators for ADSM of Consumer Electronic Products: 38th Gateway Annual Conference of Metallurgists', (Quebec City, Quebec, Canada, 22 - 26 August, 1999), pp. 425 - 439. ISBN 0-919086-93-4.

[11] Chiodo, J. D. and Billett, E. H., 'Active Disassembly using Smart Materials (ADSM), Book Title 'Green Electronics/Green Bottom Line' Butterworth-Heinemann, Fulfillment Center, 225 Wildwood Ave. Woburn, MA, USA, July 1999. 0-7506-9993-0.

[12] Yoshiki Shirai and Shunichi Hayashi, 'Development of Polymeric Shape Memory Material', Mitsubishi Technical Bulletin No. 184 (Nagoya Research & Development Center, Technical Headquarters, Mitsubishi Heavy Industries, Ltd., Nagoya, Japan, 1988), (market availability 1994).

[13] Walker, P. M. B. Ed., 'Larousse Dictionary of Science & Technology' (Edinburgh:Larousse, New York: Larousse Kingfisher Chamber Inc., 1995), pp. 479 - 480.

[14] Spillman Jr. W. B., Sirkis, J. S. and Gardiner, P. T., 'Smart materials and structures: what are they: Smart Materials & Structures, V. 5, no. 3, (Institute of Physics Publishing, June 1996) p. 248.

[15] Smart Structures and Materials 1996: Smart Materials Technologies and Biomimetics, SPIE Proceedings Vol. 2716, Editor(s): Andrew Crowson, U.S. Army Research Office, Research Trian Park, NC, USA, ISBN: 0-8194-2091-3, 360 pages Published 1996 Meeting Date: 02/25 - 02/29/96, San Diego, CA, USA, Paper #: 2716-08, pp.46-57.