

Embedding of Electronics within Thermoplastic Polymers using Injection Moulding Technique

N. J. Teh ^[1], S. Prosser ^[2], P. P. Conway ^[1], P. J. Palmer ^[1] and A. Kioul ^[3]

^[1] Dept. of Manufacturing Engineering, Loughborough University,
Loughborough, Leicestershire LE11 3TU, UK.

^[2] TRW Automotive Electronics, Technical Centre,
Stratford Road, Solihull B90 4GG, UK.

^[3] Innovative Moulding Practice Technology Division, PERA Technology Centre,
Melton Mowbray, Leicestershire LE13 0PD, UK.

Abstract

This paper reports work from a major UK research project which seeks to develop a cost effective integrated production technology for the manufacture of plastic automotive components with embedded electronics and power distribution. The said electronics sub-systems are simultaneously packaged within the automotive structural thermoplastic (TP) component during the injection moulding process. Such innovative process and product integration represents an opportunity to significantly reduce component counts and wiring loom overhead for the vehicle. The assembly, weight and cost advantages envisaged from the proposed technology will satisfy the ever-increasing demand for automotive suppliers to manufacture complete, ready-to-assemble, reconfigurable component modules with superior reliability and as such may contribute to the increased incorporation of vehicle telematics.

The paper addresses the technological and economic implications of the proposed overmoulding technology, presenting particular aspects of technological hurdles such as thermal, electrical and process requirements in the production of highly integrated polymer encapsulated electronics products. This paper highlights the findings derived from experiments undertaken to explore critical factors in the manufacture of such encapsulated electronics sub-systems, including such variables as electronics interconnection, materials selection and interactions and moulding process parameters.

Introduction

Electronic systems started to appear in significant volumes to replace electrical systems in the automotive industry during the 1960s with voltage regulators and ignition controls among the first

popular applications. However, over the past two decades legislation requirements, market-driven competition and customer demands have brought an even more dramatic increase in the incorporation of electronics within vehicles to replace many traditional mechanical or electrical systems. The growth in electronic content of a vehicle has seen an explosive rise from an average of US\$78 in 1980 to US\$861 in 1990 and thence to US\$1,495 by 1998 [1][2]. This corresponds to an increase in the average electronic cost per vehicle from 13% (1980s) to 17% (1990s) and is forecast to break into the +20% range with the addition of more software in the current decade. In the top-of-the-range cars, the electronic content can amount to 35% of the total vehicle cost [3]. Latest analysis projects a 13.4% growth for automotive electronics to reach US\$25.4b by 2003 [4] with primary adoptions to improve safety, emission, navigation and comfort.

With the distribution of circuitry, sensors and power units within the restricted space envelopes of a vehicle becoming an important limiting factor for new applications, electronic subsystems are gradually linked together to be controlled by microprocessors. This has led to the development of multiplexing concepts such as the CAN, VAN and SAE J1850 bus protocols as means of providing better data exchange and systems control with reduced harness costs.

However, as manufacturers take advantage of these multiplexed and bus architectures, electronic devices are also becoming more distributed within the vehicle. Furthermore, these complex multi-chip control systems are predominantly limited to relatively low-volume high-value cars on cost grounds. In order to fully capitalise upon the high-volume small and medium car market, a technology will need to be developed to arrive at a cost-effective means of

2000 IEEE/CPMT Int'l Electronics Manufacturing Technology Symposium

incorporating the distributed electronics, whilst at the same time producing a system with the robustness to withstand the harsh vehicle environment.

In this research project, we aim to develop a low-cost technology to embed electronics within the internal of structural thermoplastic parts that will in turn be assembled into a vehicle in the automotive industry. Figure 1 illustrates an example of such injection moulded thermoplastic parts with an embedded electronic subassembly. This proposed encapsulation technology adapts conventional techniques of thermoplastic injection moulding and electronic printed wiring board (PWB) assembly in order to achieve economical efficiency and manufacturing viability. The technique developed will also hope to bring advantages to other manufacturing sectors such as telecommunication, aeronautical, military, advanced pharmaceutical packaging and domestic applications.

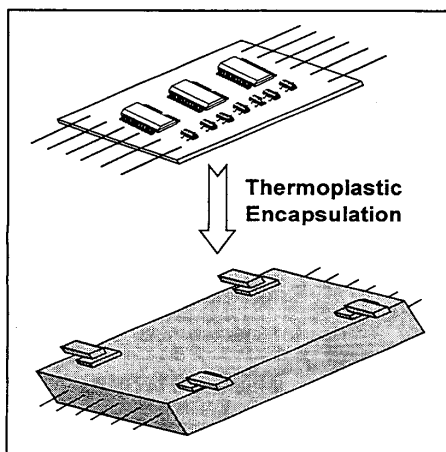


Figure 1. Illustration of the electronic overmoulding

Engineering plastics have experienced accelerated mechanical, chemical and fabrication improvements over the last few decades and feature strongly in today's vehicles because they offer geometrical design flexibility, weight reduction, lower cost and the ability to survive in exacting automotive environments.

As shown in Figure 2, injection moulding can be briefly described as a cyclic process of forming plastic into a pre-determined geometry by forcing high-temperature plasticized or molten polymer resin under an injection pressure into a specially shaped cavity (mould). The melt solidifies within the mould, which

is subsequently opened to eject the part after a given cooling time. With TP injection moulding, short processing time is achieved due to faster process cycle and no secondary operations. Also with less scrap and reusability, TP offers higher material yields.

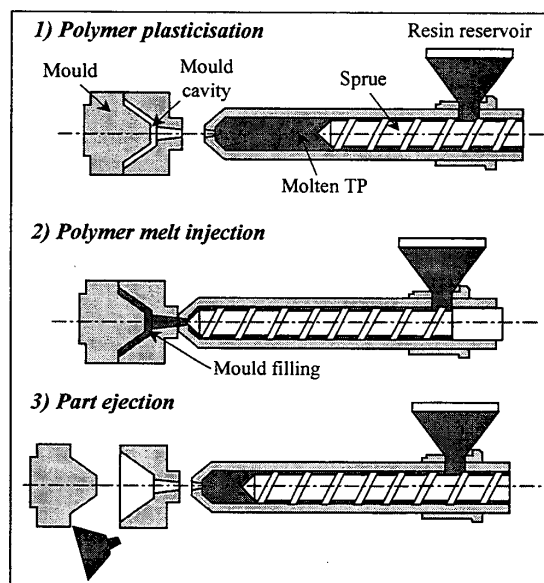


Figure 2. Schematic diagram of injection moulding

The quality and repeatability of moulded parts are predominantly influenced by a set of fundamental process parameters: temperature (melt, mould), pressure (injection, holding), time (injection, holding), speed (injection) and moulding tool design. These factors have vital and inter-related influences on both in- and post-mould reactions of the plastic part and any design flaw will result in distortion, such as thermal shrinkage, warpage, under-strength weld lines, sinks or voids in the final product.

For the success of this technology, however, the interaction between the moulding polymer and the subassembly components (particularly with PWB and electrical interconnection joints) is very important. The disparity or mismatch of material properties can cause undesired thermal shrinkage and shear stresses at interfacing layers between these materials, leading to mechanical deformations of the embedded subassembly. It is therefore critical that both optimum moulding parameters and materials matching criteria

are achieved in order to realise the manufacturability of this encapsulation technique.

Project Objectives

This project was instigated with the objective to establish an encapsulation technology that exhibits the following advantages:

- *Reduced package size.* Encapsulating electronics within structural moulding may increase functionality of the overall structure through mechatronic integration of circuitry, sensors and actuators. Additional packaging will be eliminated, ensuring minimum required space. Further package size shrinkage is possible by using mechanically or thermally folded flexible circuit to reduce the effective substrate dimensions.
- *Lower manufacturing costs.* The reduction of electronic component count and wiring loom achieved through the intelligent integration of multiple subsystems within a single structural moulding will enable the manufacture of complete, ready-to-assemble, reconfigurable electronic modules. The increase in design flexibility using thermoplastics also provides increased part consolidation. This will in turn reduce assembly time and costs in the industry to affect an even leaner and more efficient assembly.
- *Better product durability.* Provided complete interface adhesion is achieved and halides are not present in the moulding compound, plastic embedding will minimise, and even eliminate, the adverse effects of moisture, contaminant, mobile ions and radiation degradation to the performance and lifetime of the electronics. The plastic embodiment also improves the durability of the subassembly against mechanical and temperature impacts subjected by the hostile operating environments.

Improved systems robustness. The integration of subsystems within single structural moulding will significantly decrease the number of inter-connections with conventional wiring or flexible strips. The resultant improvements in system robustness, reliability, life span and size will extend the use of electronics to more potential applications such as in the more hazardous and exposed spaces of a car (wheel arch, engine bay etc.). This can further enable new packaging technologies such as chip-on-board,

multichip module, BGA and flip-chip to be used in the automotive industry for their respective and obvious advantages.

- *Product recyclability.* Unlike cross-linking thermosetting compounds used in transfer moulding, the thermoplastic materials used in this process may be recycled at the end of the product life. Figure 3 outlines such a feasible scheme for overmoulded electronic products. The recycling of populated PWBs produces copper-rich and glassfibre resin powders that are used as re-material compounds and polymer fillers respectively [5], whereas the recycled thermoplastic can be proportionally blended with virgin resin in domestic and commercial lower-grade plastic products.

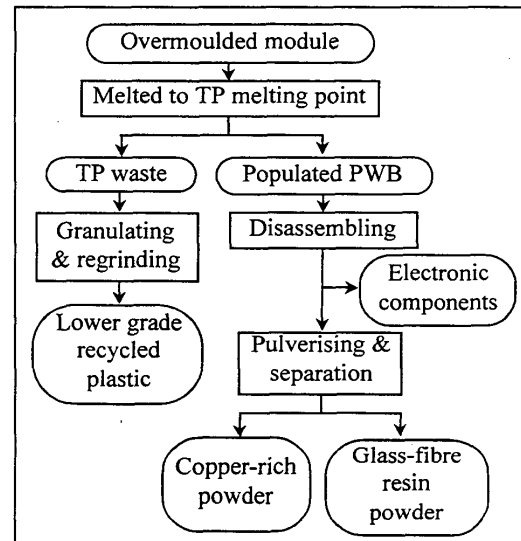


Figure 3. Recycling scheme of polymer encapsulated electronics

Problem Statement

The manufacture of the suggested plastic packaged electronic product requires in-depth knowledge in the interrelated physical and chemical reactions of electronics, material and process. Because injection moulding occurs in high temperature, pressure, viscosity (an attribute of TP) and velocity conditions, it imparts extreme stresses on the embedded assembly. Process design, including tooling layout and injection parameters (temperature, time and pressure), has to be optimised without compromising the resultant product reliability.

2000 IEEE/CPMT Int'l Electronics Manufacturing Technology Symposium

Furthermore, as the injected plastic experiences both in-mould and post-ejection residual shrinkages, the encapsulated subassembly can be subjected to localised strains leading to failures such as substrate warpage, joint fatigue and component cracking. This problem may be minimised by reducing the disparity in the linear coefficients of thermal expansion (CTE) between the encapsulant used and the embedded assembly in addition to optimising the injection process. This materials compatibility is also vital to obtaining good interface adhesion to prevent delamination-induced contamination.

Experimental Setup

The effects and influences of polymeric science, injection parameters and mould/gate geometry on qualities of injection moulded parts have been extensively investigated over recent years, primarily for intrinsic plastic moulding. These well-founded reports on customary injection moulding have become an invaluable source of knowledge to our current research. The intended encapsulation technique which embeds electronic subassembly within the plastic nevertheless carries significant deviations from conventional intrinsic moulding practice and has prompted us to design an experimental screening exploration at the outset of this project, which forms the main focus of this paper.

The main task of this experiment is to explore the technical obstacles for the process by critical appraisals of injection moulding conditions, electronics and tooling design criteria in order to identify the factors most dominant to this specific encapsulation technique. Experimental outcomes will contribute to the foundation of an optimised moulding environment non-detrimental to the embedded electronics. At the same time, other process uncertainties will also be reduced through elimination of trivial variables. To this end, we identified the following variables to be the subject of this preliminary investigation:

Polymers

Five commercial semi-crystalline resins widely used in automotive and consumer electronic applications were selected for the trials:

- *Polymer A* is a nylon polymer with good electrical properties, abrasion and chemical resistances. Its high temperature properties mean that its melt

temperature is relatively high at approximately 280°C.

- *Polymer GR-A* is a mineral-filled grade of Polymer A that has higher tensile and flexural moduli and heat deflection temperature. Its most important characteristic is the substantially lower warpage than the unfilled Polymer A.
- *Polymer B* is an unreinforced polyester grade with melt temperature of 245°C. Its good processability enables more efficient flow in thin sections.
- *Polymer GR-B* is the glass-reinforced grade of Polymer B with improved dimensional stability and surface finish, giving lower warpage and high stiffness. Its lowest processing melt temperature is 240°C.
- *Polymer C* is an acetal homopolymer that has a relatively lower melt temperature of 205°C. Its highly crystalline character suggests good dimensional stability with load and time.

Also included in experiment is the thickness (2 levels) of the polymer encapsulating the electronics.

Injection parameters

Because of the imposing effects of the individual polymer injection parameters on part shrinkages and electronic integrity, two levels of each injection setting were chosen according to the manufacturer's guidelines specific for the respective material. The moulding variable, together with the operating ranges, investigated in the experiment were melt temperature (210-310°C), injection pressure (20-110 bars), mould temperature (30-130°C) and holding pressure (30-100 bars).

Tooling design

In addition to the cavity depth variability to accommodate the two different moulding thicknesses, the position of the melt injection gate was also varied using a side gate located at the mid-point of the part length and another end gate at mid-point of its width, as seen in Figure 4.

Electronics

The electronic specimens designed for the experiment consisted of surface-mounted IC and passive components. Four pairs of metal pins that would provide electrical connectivity to the final product were soldered to the device and utilised as the support for the subassembly during the moulding process. The most important variable for the current design was the use of two types of laminate substrate, each of two

2000 IEEE/CPMT Int'l Electronics Manufacturing Technology Symposium

thicknesses of 0.8 and 1.6 mm respectively. *FR4-A1* was a conventional glass-epoxy laminate of 0.8mm thickness, while *FR4-1B* was the 1.6mm variant. *FR4-B* was higher grade of laminate in the market, with improved thermal properties such as higher glass transition temperature T_g .

A total of 22 trials were run examining 5 moulding materials, 2 wall thickness, 2 levels of 4 injection parameters, 2 gate positions and 4 different laminate substrates. For each trial, a sample size of 3 units was chosen. Table 1 outlines the complete test plan for the design of experiment (DOE).

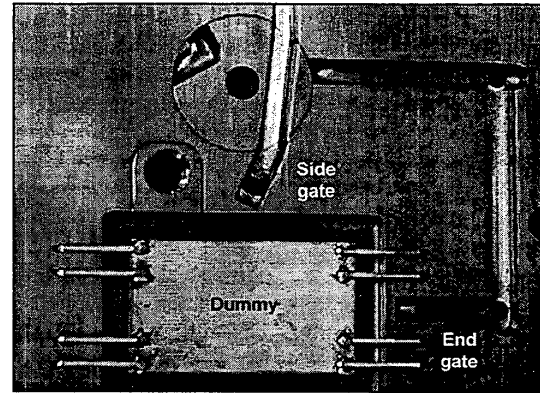


Figure 4. Injection gating design (with a dummy substrate)

Trial	Moulding Polymer	Melt Temp.	Injection Pressure	Mould Temp.	Holding Pressure	Part Thickness	Gate Position	Substrate
1	A	High	High	High	High	1	Side	FR4-B1
2	A	High	Low	Low	Low	2	End	FR4-A1
3	A	Low	High	Low	Low	1	Side	FR4-B2
4	A	Low	High	High	Low	2	End	FR4-A1
5	A	Low	Low	Low	High	1	Side	FR4-A2
6	GR-A	High	High	Low	High	2	End	FR4-B1
7	GR-A	High	High	Low	High	1	Side	FR4-A1
8	GR-A	High	Low	High	High	2	End	FR4-A2
9	GR-A	High	Low	High	Low	1	Side	FR4-A2
10	GR-A	Low	Low	High	Low	1	End	FR4-B1
11	B	Low	High	High	High	1	Side	FR4-A1
12	B	Low	Low	High	Low	2	End	FR4-B2
13	B	Low	Low	Low	Low	2	End	FR4-A1
14	GR-B	High	High	High	High	2	Side	FR4-B2
15	GR-B	Low	Low	Low	Low	2	Side	FR4-B1
16	C	High	High	High	Low	1	End	FR4-A2
17	C	High	Low	Low	High	2	Side	FR4-B1
18	C	High	Low	Low	High	1	End	FR4-B1
19	C	Low	High	Low	High	2	Side	FR4-A2
20	C	Low	High	Low	High	1	End	FR4-B2
21	C	Low	Low	High	High	1	End	FR4-A1
22	C	Low	Low	Low	Low	2	Side	FR4-B1

Table 1. Experimental design plan

Result Analysis

As this exercise was primarily designed to investigate mechanical failure mechanisms, the overmoulded specimens were subjected to the following evaluation processes:

- a) X-ray radiography to detect solder joint damage, component damage and displacement and also substrate deformations.
- b) Length-wise moulding warpage was measured to account for deformation resulted from thermal shrinkage and inapt process design.
- c) The overmoulded parts were cross-sectioned to reveal the embedded subassembly. Through the inspection of sectioned specimens, the distortions to the solder joints and laminate substrates were rated against specific weighting scales.

A statistical analysis of variance (ANOVA) for each defect was utilised to interpret the results from the DOE. An ANOVA breaks down the process perplexity and identifies the percent contribution of the individual sources of variance to the total variance. Table 2 lists the results from the ANOVA carried out for each defect mechanism evaluated in this exercise. The first column in this table lists the defects evaluated, the second column (Source of variation) lists the variables examined in the model and the third column displays the sum of squares for each effect. The mean square of each effect is calculated by dividing the sum of squares by its degrees of freedom. Subsequently an analysis of means (ANOM) was performed for each of major parameters nominated by ANOVA to identify the optimum level for minimum defect of the moulding.

Results Summary

From the results of ANOVA in Table 2, the variance contributing factor demonstrated by individual process variables on each of the failure mechanisms was broken down.

Solder defect

Polymer variable provides nearly 45% of contribution to the solder defect ANOVA. From the results of ANOM, the reinforced GR-A and GR-B were found to have displayed 5% and 20% less solder defects over their respective unfilled counterpart. However, the lower melt temperature polymer C was found to be the least hostile to the solder joints by producing nearby 10% and 45% less defects than polymers GR-A and GR-B, respectively.

Other important contributing factors identified were the melt and mould temperatures. The combination of high mould temperature, low melt temperature and low injection pressure was found to be the best injection condition with respect to solder defects. This condition was thought to enable pre-heating of the subassembly before an injection with molten polymer at a lower temperature and injection force. In this case, the thermal shock suffered by the subassembly would be considerably reduced.

Module deflection

Warpage of intrinsic polymer moulding is a well-established and widely reported issue with polymer properties, injection parameters and tooling geometry amongst the commonly known causes. In the process investigated here, however, the parity of the CTE between the moulding polymer and substrate laminate becomes another major factor. Figure 5 below shows two specimens with different degrees of longitudinal warpage observed during this experiment. Using a digital imaging system, deflections between 0.13-1.20mm over a linear dimension of 60mm were measured. As predicted, the ANOVA has shown that the polymer (42%), part thickness (32%) and laminate substrate (7.4%) were the most dominant variables for part deflection.

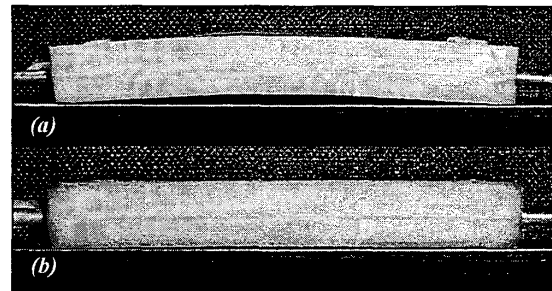


Figure 5. Warping of injection moulded module

From the mean analysis, the glass-reinforced semi-crystalline plastics GR-A and GR-B showed mean deflection reductions of approximately 37% and 48% over their respective unfilled polymer. This can be attributed to lower linear CTE difference, increased dimensional stability, homogenous crystallised nucleation and shorter crystallisation time with the presence of fillers. Polymer C, with higher crystallinity, undergoes a much higher density increase upon solidification and hence more shrinkage. Overall polymer C produced 16% and 18%

2000 IEEE/CPMT Int'l Electronics Manufacturing Technology Symposium

0-7803-6482-1/00/\$10.00 ©2000 IEEE

higher longitudinal deflection than the unfilled polymers A and B respectively. GR-B was found to be the most promising resin in this respect.

The ANOM results showed that thinner moulding produced a mean reduction of 41% in longitudinal warpage. This is due to the shorter solidification cycle

required for the lower wall thickness. Also, with higher flexural modulus, FR4-1 laminates showed lower warpage over FR4-2. However the thinner 0.8mm substrates were found to have produced 36% (FR4-1) and 7% (FR4-2) less deflections than those of 1.6mm substrates.

Defect Mode	Source of Variation	Type III Sum of Squares	Degree of Freedom	Mean Square	F-Test Statistic	Percent Contribution
Solder Joint (Adjusted R ² =0.872)	Moulding Polymer	2412.509	4	603.127	2.47	44.62
	Melt Temperature	41.366	1	41.366	0.17	0.77
	Injection Pressure	51.279	1	51.279	0.21	0.95
	Mould Temperature	565.873	1	565.873	2.32	10.47
	Holding Pressure	2.615	1	2.615	0.01	0.05
	Part Thickness	6.843	1	6.843	0.03	0.13
	Injection Gate Position	276.628	1	276.628	1.13	5.12
	Substrate Laminate	113.746	3	37.915	0.16	2.10
	Melt Temp*Inj Pressure	43.199	1	43.199	0.18	0.80
	Melt Temp*Mould Temp	671.691	1	671.691	2.75	12.42
	Inj Pressure*Mould Temp	1.100	1	1.100	0.00	0.02
	Error	1219.411	5	243.882		
Total		5406.259	21			
Part Deflection (Adjusted R ² =0.951)	Moulding Polymer	4021.651	4	1005.413	7.80	42.11
	Melt Temperature	27.478	1	27.478	0.21	0.29
	Injection Pressure	34.729	1	34.729	0.27	0.36
	Mould Temperature	138.601	1	138.601	1.08	1.45
	Holding Pressure	131.185	1	131.185	1.02	1.37
	Part Thickness	3061.619	1	3061.619	23.77	32.06
	Injection Gate Position	676.553	1	676.553	5.25	7.08
	Substrate Laminate	707.303	3	235.768	1.83	7.41
	Melt Temp*Inj Pressure	70.572	1	70.572	0.55	0.74
	Melt Temp*Mould Temp	8.960	1	8.960	0.07	0.09
	Inj Pressure*Mould Temp	28.197	1	28.197	0.22	0.30
	Error	644.099	5	128.820		
Total		9550.945	21			
Substrate Distortion (Adjusted R ² =0.746)	Moulding Polymer	1241.933	4	310.483	0.68	15.36
	Melt Temperature	230.784	1	230.784	0.51	2.85
	Injection Pressure	200.519	1	200.519	0.44	2.48
	Mould Temperature	121.340	1	121.340	0.27	1.50
	Holding Pressure	328.013	1	328.013	0.72	4.06
	Part Thickness	0.744	1	0.744	0.00	0.01
	Injection Gate Position	165.173	1	165.173	0.36	2.04
	Substrate Laminate	2825.957	3	941.986	2.07	34.96
	Melt Temp*Inj Pressure	61.390	1	61.390	0.14	0.76
	Melt Temp*Mould Temp	633.608	1	633.608	1.39	7.84
	Inj Pressure*Mould Temp	1.290	1	1.290	0.00	0.02
	Error	2272.890	5	454.578		
Total		8083.639	21			

Table 2. ANOVA results for thermoplastic injection moulding of electronics

Substrate distortion

Our work on FEA modelling of the encapsulation process [6] has discovered that the pressure distribution in the mould cavity resulting from the advancing flow front produced a pressure difference of approximately 1MPa (10 bar) between the top (with components) and the bottom surfaces of the subassembly. The resultant net force caused deflection to the substrate in the direction of this pressure difference. The x-ray image of two samples in Figure 6 show the extents of distortion that can be incurred to the laminate substrate.

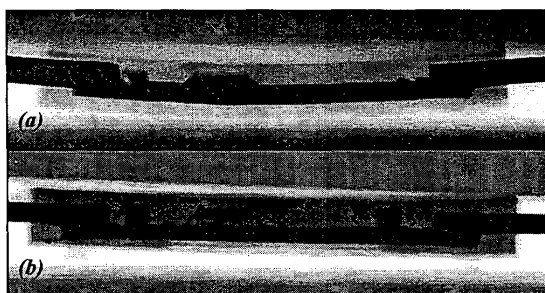


Figure 6. Distortion of the embedded subassembly

From the ANOVA table above, the main contributing factors to substrate deformation in the moulded parts are laminate itself (35%), polymer (15%), and melt temperature*mould temperature (8%). Also the injection pressure was quite significant.

The subsequent ANOM predictably showed that the higher T_g FR4-B laminates suffered less severe deformation. However the improvement became less significant as the substrate thickness increased. The 0.8mm FR4-B deformed 48% less than 0.8mm FR4-A, but this difference decreased to only 1% for the 1.6mm laminates. In this respect, a within-grade comparison showed the 1.6mm FR4-A was nearly 50% better than the same material of 0.8mm thickness, and this again decreased to just 2% for the FR-4B laminates. Overall, there was not much to choose between 1.6mm FR4-A and FR4-B in this evaluation. However the former is substantially lower in cost and more readily available.

Our initial work had shown that improvement would be obtained with the glass-reinforced polymers. However in this was not observed in this experiment. The current analyses indicated that unfilled polymers

A and C were the two most optimum grades and this result discrepancy will be further investigated.

For minimum laminate distortion, the conditions with low melt temperature, high mould temperature and low injection pressure were found from the ANOM to be the most favourable injection condition.

Conclusion

The experiment conducted here has formed an effective screening exercise for the various variables and unknown factors involved in the process of electronic encapsulation with conventional injection moulding technique. We have managed not only to identify the dominant process factors and suitable elements, but also eliminated trivial variables. By contributing to most of the variance in three defect categories, moulding polymer has proved to be the most influential variable in the process.

Our latest work has very significantly minimised the deformations discussed in this paper through systematically designed process improvements. The process will be more critically and functionally investigated with the injection moulding of an instrumented circuitry coupled with real-time data acquisition.

Although our current work has been concentrated on low power automotive applications, we have thus far demonstrated a feasible low cost encapsulation technology that is lean and economical to the automotive industry.

References

- [1] Yanik, J.A. "The Automobile: Unwanted Technology-The Later Years, Part II: The Downfall of Automobile Electronics." *Automotive Electronics: The 1990's*. 1998. pp 213-233.
- [2] Harkness, E. "Automotive Electronics in Europe – Success in a Changing Market." 1995.
- [3] Frank, R., Shukman, H. "Electronics and the Digital Car of the Future." *Automotive Electronics: The 1990's*. 1998. pp 515-526.
- [4] Brancato, R. "Millennium Prediction: A Package for All Occasions." *Advanced Packaging*. Vol. 9, no. 1, January 2000. pp 30-34.
- [5] Yokoyama, S., Iji, M. "Recycling System for Printed Wiring Boards with Mounted Parts." *NEC Research and Development*. Vol. 39, no. 2. 1998. pp 111-115.

[6] De Cooper Jones, M. Project Interim Report, June 1999.

Acknowledgements

The authors would like to extend their gratitude to the personnel at Pera Technology Centre, TRW Automotive, Tunewell Technology Ltd., and Middlesex University who have made significant contribution to this project. This work is jointly funded by the United Kingdom DTI and EPSRC under the Foresight-Vehicle programme.

Biography

Nee Joo Teh graduated from Tunku Abdul Rahman College, Malaysia in Electronic Engineering. His industrial experience began as a Trainee Engineer at Intel Technology, Malaysia and later as a Maintenance Engineer. He received his MSc from De Montfort University and followed by further research work. He joined Loughborough University in 1999 as a Research Associate to work on a Foresight LINK Vehicle research project. His research interests include electronic packaging, interconnection, manufacturing and mechatronic systems.

Steve Prosser graduated from Oxford University with a degree in Chemistry and PhD in physical sciences. His industrial career started with THORN EMI Central Research Laboratories before joining Lucas (now TRW) in 1985. He is currently the Technology Manager for TRW Automotive Electronics, responsible for the development of advanced electronics and sensors for automotive applications. He is also the current Vice Chairman of the Institute of Physics Instrumentation Science and Technology Group and Visiting Professor of Engineering at Lancaster University.

Paul P Conway graduated from the University of Ulster with First Class Honours and with the Inst. of Production Engineers' Shorts Bros. PLC prize. He later received his MSc from Loughborough University where he is currently a Reader. He has previously worked as a Research Assistant on a project on process modelling of reflow soldering and as an Industrial Engineer with Fisher Body Overseas Corp., General Motors Corp. He has held a number of substantial UK, European and industrially funded research projects and has published widely in the field of electronics manufacturing and micro-systems technology.

Paul J Palmer is a Senior Research Fellow at Loughborough University. He has interests in electronics, design and manufacture with particular reference to cost and green design issues. His industrial career has been based in manufacturing as an Engineering Manager for Hawker Fusegear and forging industry-academia links as a Senior Teaching Company Associate with the University of Salford. He graduated from University of London and gained MSc from Cranfield Institute of Technology.

Azzedine Kioul obtained his BSc from the Algerian Institute of Petroleum. His experience started as a technical engineer at an Algerian polymer company and later as a research scientist at the IPTME, Loughborough University, from where he received his PhD. He is currently a Technical Consultant at Pera Technology Centre. His work includes In-Mould Labelling and RFI shielding, selective plastic plating, smartcard manufacture and innovative injection moulding. He is also an affiliate member of the Society of Plastics Engineers and listed in the Technomic Who's Who in plastics.