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Partners:
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HEK GmbH
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RTM
DTI
LEGO A/S

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RAPITOOL BE 5929

Thierry Dormal, Umberto Baraldi
CRIF Technologie des Matériaux
Rue Bois Saint-Jean, 12
B 4102 Seraing BELGIUM

Herman Nollet
ALCATEL BELL
Berkenrodelei 75
B 2660 Hoboken BELGIUM

Gerhard Shroeder
HEK GmbH
Kaninchenborn 24-28
D 23560 Lubeck GERMANY

Kevin McAloon
ZENECA Limited
PO Box 8 The Heath
GBWA74QD Runcorn Cheshire ENGLAND

Eduardo Vila
Mares CM
Poligono Industrial La Ferreria 14
ES 08110 Montcada I Reixach SPAIN

Philippe Orlians
Orlians NV
Populierendreef 35
B 2800 Mechelen BELGIUM

Lorenzo Bonello
RTM
Reg. Kime Vico Canavese
I 10080 Torino ITALY

Niels Moos
DTI
Teknologieparken
DK 80000 Aarhus DENMARK

Egon Skivild
LEGO Engineering
DK 7190 Billund DENMARK

ABSTRACT

This report describes the work carried out during the BRITE EURAM project BE 5929 "RAPITOOL". The objective of this project is to develop and qualify economical fabrication methods for thermoplastic injection moulds manufacturing. Four different methods, all based on the availability of RPT (Rapid Prototyping technologies) models, are developed to offer substantial cost and delays reduction for the realisation of prototypes or short run injection mould cavities.

Actual classical methods provide either unacceptably high costs and delays or heavy limitations regarding precision of geometry complexity. Specific capabilities of the considered techniques or their combination provide solutions for manufacturing complex cavities for production runs of 100 to 5000 parts.

INTRODUCTION

Four specific techniques are considered in Rapitool. Each technology shows different requirements and possibilities in terms of geometry complexity, dimensions, delays, costs and number of parts in the pre-series. The developments and the technico-economical conclusions are described here.
The technical description , the results and the conclusions are described here separately for each technique.
Several difficulty classes are defined for each technology. The different parts are
- Simplified Lego bush (60*55*25 mm).
- Same Lego bush with ribs.
- Same Lego bush with ribs and cores.
- Boat engine cover (510 * 310*80 mm).

Technique 1: Direct RPT Cavity

Summary
The iterative optimisation of resin formulations prepared in ZENECA's laboratories and evaluated by the Danish Technological Institute led to the identification of the candidate tooling resin ZRP95/17, which when processed into cavity shells, proved capable of producing 95 replicate models by injection moulding with ABS/polypropylene. The continuation of the Research Programme within ZENECA is to proceed in cooperation with several SLA service centres and interested industrial parties. A Commercial Exploitation plan has been implemented.

Objectives
- To develop cavity manufacturing techniques making direct use of cavity shell realised by Stereolithography (SLA) RPT technique.

- To develop stereolithography resins for processing into cavity shells which will withstand repeated injections of a thermoplastic polymer. Life expectancy of the shell should allow up to 250 parts in polypropylene or ABS polymer.

Work Programme
-1 Optimisation of Resin Formulations
-2 Development of Cavity Manufacturing Techniques

Technical Report

1 Optimisation of Resin Formulations

Precedent scientific and patent literature was searched and collated. A current awareness profile was updated (Derwent Alerts) at two-weekly intervals throughout the Project.

1.1 Resin properties

Target resin properties were established to enable selection of candidate resins for further testing by Stereolithography. Key resin parameters were seen as:- viscosity, volatility, cure speed, cure shrinkage, tensile modulus, tensile strength, elongation at break, impact and heat-shock resistances; stereolithography processing parameters evaluated by the Danish Technological Institute were Ec, Dp, CF6 curl factor and build times. Suitable resins were then used to prepare cavities which were tested in an injection moulding machine by LEGO (Denmark)

1.2 Results

Refinements in acrylate resin formulations (different oligomers, crosslinkers, etc) proved capable of producing resins which could withstand the injection moulding environment for up to 40 "shots".

Addition of organic fillers or low-functionality organic polymers to resin formulations offered no further advantages in the durability of the cavity.

Inorganic layer minerals imparted excellent improvements in impact and heat-shock resistances when added to acrylate resins without impairing the key stereolithography processing parameters.

After optimisation of the amount of filler required (maximum'% wt filler /resin to give acceptable viscosity and minimum settling out), a candidate ZENECA tooling resin has recently emerged. A comparison of processing properties is given in **Table 1**

1.3 Comparison of initially planned activities with work accomplished

The overall technical target was to develop a stereolithography resin capable of being processed into RPT cavities which could then produce up to 250 replicate models in polypropylene or ABS thermoplastic polymer.

To accomplish this target resin properties were identified and inevitably modified as the project progressed. The candidate ZENECA *tooling resin* which has emerged does not at present appear to be capable of producing 250 replicates **in ABS,** but further iterative optimisation of the formulations is continuing at ZENECA and further improvements in cavity design (e.g. incorporation of metal support structures into high stress areas) could well enable the attainment of the required resin shell durability.

2 Development of Cavity Manufacturing Techniques

2.1 Activities

Development of a technique for manufacturing of RPT shells used as cavities in injection mould tools involves a number of activities:

-Translation of CAD data describing the final 'part to CAD data defining the shells,
-Modelling of parts and shells in 3D CAD
-Building of shells in SLA
-Building of moulding tools in different materials
-Definition of SLA working parameters,
-Determination of backfilling material,
-Cavity structure modifications,
-Injection mould test for verification of method,
-Test of different surface treatment techniques.

2.2 Progress

Throughout the project a comprehensive number of injection mould tests were performed. **Table 1** on page 8 is giving an overview of these tests and their main results.

2.3 The "LEGO BUSH"

The basic idea in task2 was -based upon the model of a part- to build two shells describing two parts of a cavity for injection moulding. These shells might afterwards be supplemented with supports for backfilling.
At an early stage in the project it was decided to use "The Bush" from Lego as a common test part for all techniques and all difficulty classes. The difference between difficulty class I and II was to be realised through exclusion/inclusion of a number of details like ribs, inserts, etc. In this way a number of different "Bushes" were created, some of those had no similarity with the original, however contained the same kind of intricate details and difficulties,

The purpose of the design was to facilitate easy change of variation of geometrical parameters
-split parting planes
-shell thickness
-injected materials
draft and draftangles,
etc.

The result of the tests was a very good understanding of the influence of the process parameters.

3. Comparison of initially planned activities with work accomplished

The overall technical target was to develop a stereolithography resin capable of **being** processed into RPT cavities which could then produce up to 250 replicate models in polypropylene or ABS thermoplastic polymer.

To accomplish this target resin properties were identified and inevitably modified as the project progressed. The candidate ZENECA tooling resin which has emerged does not at present appear to be capable of producing 250 replicates in ABS, but further iterative optimisation of the formulations is continuing at ZENECA and further improvements in cavity design (e.g.incorporation of metal support structures into high stress areas) could well enable the attainment of the required resin shell durability.

4. Conclusions

4.1 Optimisation of Resin Formulation

Iterative optimisation of resin properties resulted in a ZENECA candidate tooling resin capable of allowing the production up to 100 replicate models in ABS/polypropylene by injection moulding. Although this result fell short of the target (250 parts), the knowledge and insights gained during the project will provide "a clear strategy for producing a tooling resin capable of surpassing the required standards. The project is to continue at ZENECA under internal funding.

Recent reports (Ref. 14) indicated that the Japanese Company Teijin Seiki have already produced a filled SL resin capable of fulfilling the above target specifications. A search of the patent literature has furnished several relevant patents (Refs. 15-17).

It is already clear that in order to develop a similar tooling resin, it will be essential to work in close collaboration with experts in the use of stereolithography apparatus so that modifications to both resin and processing parameters can progress in tandem.

4.2 Cavity Manufacturing Techniques

The methods which are used in technique 2 seems promising, however design and building of SLA shells with a positive model of the bush as starting point showed difficulties within...

- Tolerances of the CAD model have a great influence when transferring via IGES.
- The geometry that is transferred via IGES often has to be modified manually before use in the receiving CAD system.
- Automatic generation of wall thickness is not possible by complex geometries.
- Many considerations are needed before the optimum design of the shell is reached,
- Anchoring of the shell in the backfilling material is important and has to be done with great care.
- Certain details can not be included in the mould process.
- Ejectors, runners and other functional elements have to be taken into account in the design of the shell,

The technique will be further investigated.

Technique 2: Two axis laser cutting.

SUMMARY

The goal of this task is to develop a new manufacturing technique for low cost prototype moulds. We call this technique LLCC (Laminated Laser Cut Cavities).
A software was implemented to slice the shells of the moulds into 2D contours with specific filters and corrections adapted to the laser cutting process. Three partners tested this laser cutting operations and produced numerous LLCC moulds. Several stacking and assembly techniques were tested in conjunction with other technologies (investment casting, metal sistering,...) to produce hybrid prototype moulds. Finally thousand of thermoplastic parts were injected in these different moulds.

OBJECTIVES

The main goals of this task are:

- To evaluate and develop a cavity manufacturing technique combining general form generation by stacking laser cut steel plates and surface finishing by resin or other techniques.
- To define all basic requirements concerning CAD files preprocessing, CAM files generation and plates assembly techniques.

TECHNICAL WORK AND RESULTS

Operational sequence for Laminated Laser Cut Cavities (LLCC) fabrication.

The different operations needed to realise an LLCC are the following ones:

1. CAM files generation.

A specific software developed at CRIF reads the STL file of the shells and produce the successive layers to be cut by the laser with an adapted repartition on a steel plate.
Several functions and parameters allow the production of 2D contours easily used by the laser systems without additional pre-processing:

- Automatic closing of all the contours.
- Near points filtering (minimum distance between 2 successive points).
- Collinear points filtering.
- Visualization in different colors if several contours appear for a giveri Z value.
- Interactive visualization of each successive contour with the corresponding parameters (Z value, number of points, coordinates of starting point,...) for contour checking.
- Interactive visualization of each successive plate for global contour checking.
- Information tools about the content of the STL file: minimal and maximal values in X,Y and Z, number of triangles,...
- Several ranges with different thicknesses.
- Thickness offset for accuracy adaptation.

2. Laser machining.

Numerous laser cutting operations were performed with RTM, Orlians and Alcatel to reduce the pre-processing time of the files and the laser cutting time. In the mean time the quality of the contours was enhanced to reduce the postprocessing operations on the cut sheets.

3. Surface finish, stacking & assembly procedure.

To maintain mechanical coherence of the LLCC foils, simple clamping has been found to be insufficient., Therefore, numerous bonding tests were performed with different bush geometries, the main criteria being ease of use and binding zone thickness controllability.
The materials were anaerobic adhesive, adhesive with glass bails, adhesive film, epoxy and silicon adhesive.
The anaerobic adhesive appears as the best solution in terms of processing. and accuracy and will be used in the future. The tensile shear strength tests proved also the good behaviour of this adhesive.

The different brading and welding techniques considered have all proved to be very interesting in terms of mechanical properties improvement, but to result in a non negligible cost increase of the whole process.
Nonetheless, the frost tests carried out with the last three techniques were encouraging enough to require further development.

In order to improve the stacking procedure of the metal foils, a special stacking system has been devised to solve two main problems:

- Definition of the referencing strategy for the centering of the foils
- Definition of an integration system in a mould frame

Different solutions were used in parallel during the project for finishing:

- resin layer on the steel sheets to fit exactly on the real surface.
- manual finishing.
- EDM finishing for parting plane.

4. Core and Cavity fabrication.

Relying on the experience gathered in the former tasks, practical testing and mould fabrication was realised for a large set of test tools.
In the Lego Bush, two complex small details are difficult to build with LLCC, even if the layer thickness is 0.3 or 0.5 mm. So we decided to try an hybrid technique:

- LLCC for cavity and external core.
- Metal part to be inserted in the core. This part include the two small complex details
  This metal part was produced by two different techniques:
  - Stereolithography part+ investment casting (XC).
  - Direct metal sintering with the new EOSINT M process.

This last technique allows a good accuracy and short building time.

5. Injection moulding.

The real injection test of the moulds have been realised on current 90 tons computer controlled injection machine. The moulded material is an ABS grade, typical of the applications of one of the industrial partners.

With simple geometries (bush with ribs but no cores), the solution LLCC with resin layer in the cavity is able to give more than 700 injected parts.
The complex bush mold was not perfect in terms of draft angles and limited the number of injected parts to 250 but the integration of the inserts (IC and EOSINT M) in the LLCC proved perfectly safe and problemless.

CONCLUSIONS :

CAM files generation for LLCC, using our slicing software is now operational and perfectly adapted to laser cutting machines. The preprocessing is quick and easy and the laser cutting process is optimal.
The quality of the laser cutting may vary and lead to very small but troublesome undercuts in the cavities of the mould.

The glueing and assembly techniques are valid but time consuming. Automation of stacking and centering procedure has to be enhanced to reduce both delays and costs.
The cavity surface finishing by resin layers has been enhanced during the project but the time life of such a mould with resin layer is difficult to guarantee, the risk of cavity destruction in the first 20 shots being unacceptably high.
The quality of the parting plane realised by cavity/core respective EDM has proved to be perfectly satisfactory.

The number of produced parts before breakdown is really significant (>500) if specific rules are followed:

- minimal draft angles in CAD definition.
- prudent ejector drilling.
- no undercut due to bad laser cutting.
- no resin finish

The number of plastic parts produced with the mould is higher and more predictable than in an epoxy mould. The following table shows the results of an economical comparison performed for the different tool types that were realised, the industrial partners providing significant data on state of the art costs.
Considering the Bush part, cost advantages of LLCC in comparison to conventional techniques is not important enough to justify the geometrical and qualitative limitations of this technique. Important benefits in delays reduction can nonetheless be a decisive factor.
For such small parts, the concurrence of the new metalsintering techniques seems to be a non negligible threat.
The hybrid solution between LLCC and metal sintering seem to be a good compromise for the future of rapid tooling in terms of price and delays if the geometry includes large simple zones of geometrically simple shapes combined to complex intricated details.
On the other hand, LLCC appears to be economically viable for large moulds. This technique should be mixed to metal sintering or NC machining of complex cores or parts od moulds, but the potential costs and delays savings are very imporant (more than 60% savings).
Future developments should include:

- Improvement of parting plane generation.
- Improvement of surface finishing.
- Automatisation of the assembly process.

Technique 3: Five axis laser cutting.

OBJECTIVES

The Technique 3 objective was the evaluation of the use of 5 axes laser systems in cutting slices , with inclined cut face, so to avoid or limit the steps that are typical of objects obtained by stacking techniques.
These steps are a carachteristics of 2 axes cutting , where only thickness reduction can reduce the steps evidence , but not to eliminate them..
This verification can be performed through the realization of objects (prototypes) of different complexity, in the same time evaluating different possibilities present on the market.
Two dies of different complexity level were defined as comparison tests.

TECHNICAL WORK AND RESULTS

The simplest one was formed by the two pints of a die, named “ Core and Cavity”, of very simple shape, and designed by a simple sketch reporting only general dimensions.
The corresponding two sets of slices (one for the punch, or Core, one for the matrix ,or Cavity) are formed of similar elements , differing only a little in the dimensions , of the order of about 30 each one,
The second one , named Lego bush, due to its origin, is made of two parts again, each one of 94 slices, some of very simple shape, a rectangle, the other ones, the most interesting, with shapes of different complexity, representing the sections of the die with parallel planes.
These parts are described by STL files , as requested by the Rapitool assumptions. The same parts are used in the 2 axes cutting (task 3); so a comparison is possible.
The difference with 2 axes cutting lies in the way the files are used . In 2 axes cutting theslice obtained is supposed to be the copy of the component represented in the file ; in 5 axes cutting the component results from the action of the laser beam which must match two adiacent profiles (slices of the 2 axes solution), therefore beam orientation in the space changes continuously.
The CAM programs are very different.The Core and Cavity sample requires a simple list of instructions, referring to the laser beam orientation along the 4 sides, and the variations approaching the comers , to obtain well specified comers fillets shapes.
The different slices repeat the same figure with little modification, the same each slice. For a given thickness lasewr parameters are the same for all the slices of Core and Cavity.

The Lego Bush is represented by files which are the basis for the CAM elaboration, able to set cutting parameters, based on fixed laser parameters.
An algorithm was defined , able to control the lasaer focus position , a necessity in laser cutting, and connect the supposed corresponding pointsof the two files representing the upper and the bottom profiles of a slice.
Adoption of this simple operations required a large amount of the PC memory for the simplest shapes yet and operations appeared very cumbersome.

With reference to the laser system, the program was to ceompare the RTM's system results with some diffused commercial solution..

RTM system resulted soon unsuitable due to its architecture. It resulted affected b y unacceptable imprecision and vibrations, due to the cutting speed and dimensions of moving parts, in spite of important modifications of the head. As a consequence most of the tests planned in RTM were transferred to external systems.

These tests confirmed the limitation of the cutting angle , about 18°, a constant for the systems tested.

Core and Cavity prototype was obtained in several solutions of materials and thickness, because the largest angle required is not higher than 10°. Even the results appear quite satisfying, surely superior to 2 axes cutting results, some improvement seems possible.

Lego Bush example instead resulted too difficult for a normal 5 axes system, and it resulted impossible to obtain a good solution with the ususal procedures.

Problems relate to:

- angle of cutting,
- vibration induced by fast movements,
- movement abrupt interruption do to PC block (memory paralysis due high amount of orders).

Alternative solutions were found in a complex cutting procedure, consisting in a 2 axes cutting followed by a edges beveling, tried in two ways, 5 axes fro the reverse side and caving.

Results are close to be acceptable ; some hand correction appears sufficient to make the results fully acceptable, surely room fpr improvements exists.

Another solution was tested : a 6 axes system , which resulted quite good in the preventive tests with simple samples , but became unacceptable for more complicated shapes , as Lego Buush die, due to the very large amount of CAM software elaboration required.

The inquiry for a solution made extend activity on market contacts, therefore large attention was payed to:

- laser systems suppliers,
- job- shops
- Research Institutions, both Public and Private.

CONCLUSIONS :

Results confirm the RTM experience that can be summarized as follows.

Stacked objects construction depends on its complexity: simple prototypes can be made , with the only limitation of the cutting angle (18° max); more complex shapes can find limitations in CAD CAM programmingg and system architecture.

The costs are in line with the same complexity problems, requiring heaviest programming work.

In the field of forecasts, success is possible, depending on improvement of laser sources, so to dispose of high quality beams connected with better systems solutions as offset, exapod, and so on. Beside a larger cooperation would be useful to overcome software problems.

Technique 4: Low melting point metal casting.

SUMMARY

Low melting point metal (LMPM) cavities or inserts are cast in soft moulds and are integrated to injection moulds.

OBJECTIVES

The main objective is to develop a technology for very low cost cavities manufacturing of limited series of complex parts with specific demoulding and surface aspects requirements. Using simple tools and within a short time (max. 5 days) it is possible to produce a serie of original material components using a stereolithography model.

TECHNICAL WORK AND RESULTS

The successive working tests to produce this type of mould **is the following:**

- SLA Model building.

Day 1 Step 1
Produce silicone mould using MCP Vacuum Casting System. Overnight cure

Day 2 **Step** 2
Produce working prototypes using MCP Vacuum Casting System

Day 2 **Step** 3
Produce high temperature Epoxy Resin EP 180 castings of silicone vacuum casting mould . Overnight cure.

Day 3 **Step** 4
Cure high temperature resin -2 stages

Step 5
Cast MCP lo alloy again high temperature EP 180 mould models.

Day 4 Step 6
Machine injection gate,
if necessary drill holes for ejectors and cut ejector pins to lenght.

Step 7
Produce mouldings

CONCLUSIONS

The economical results of such a mould is a cost approximately 4% of the conventional steel mould.

Acknowledgements

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17. JP07026062, 27/01/95; Application Nos JP 93196691 and 2, 15/07/93: TEIJIN-SEIKI; SL Resin containing inorganic needles eg Al Borate + (optional) organic high polymers

18. "Investigations on the Influence of Material and Process on Part Distortion". B. Wiedernann, K-H Dusel, J Eschl: 4th European Conference on Rapid Prototyping and Manufacturing; Institute for Polymer Testing and Polymer Science, Dept of Polymer Engineering, IKP - University of Stuttgart, Pfaffenwaldring 32, D-70569 Stuttgart, Germany. Editor, Dr PM Dickens, University of Nottingham, England

Table 1: Comparison of resin properties

Resin	XB5149 Ciba-Geigy	XB5170 Ciba-Geigy	ZRP93/9 Zeneca	ZRP95/16 Zeneca	ZRP95/17 Zeneca
Type	acrylate	epoxy	acrylate	acrylate	acrylate
Viscosity @ 30°c	2150 mPa.s	180 mPa.s	360 mPa.s	780 mPa.s	2800 mPa.s
Lin Shrnkge on cure	2.0390	1.50 %	2.17 %	1.90 %	1.66 %
Heat shock resistance	50 (5/5)	50 (5/5)	50 (4/5)	50 (4/5)	50 (5/5)
Impact resistance	22 kJm^{-2}	27 kJm^{-2}	8 kJm^{-2}	18 kJm^{-2}	29 kJm^{-2}
Tensile modulus	600 MPa	1200 MPa	400 MPa	655 MPa	1195 MPa
Tensile strength	24 MPa	50 MPa	17 MPa	27 MPa	39 MPa
Elongation @ break	12%	10%	7.2 %	10.2 %	6.9 %
Ec	6.6 $mJcm^{-2}$	13.5 $mJcm^{-2}$	5.8 $mJcm^{-2}$	10.7 $mJcm^{-2}$	3.7 $mJcm^{-2}$
Dp	7,3 mils	4.8 mils	5.2 mils	12.8 mils	5.8 mils
IM Replicate models	-	50+	40	27	95
Build Time 30mmx30mm x 1layer	10 sees	57 sees	8 sees	8.5 sees	8.5 sees
Comments			1 St generation resin	Base resin for ZRP 95/17	Filled resin

APPENDIX 1

PUBLICATIONS

1. “Selection of Stereolithography Resins for Injection Moulding Cavities”
J Lawson and KT McAloon; EARP Newsletter No 6, July 1995, p12.

CONFERENCE PAPERS

1. "Stereolithography resins for rapid prototyping" - Poster presented at internal ZENECA Resins Symposium, 11-12 Ott 1994
2. “Rapid Prototyping for Tooling Applications” -JR Lawson, Rapid Prototyping Research Forum, Cranfield University, 10th July 1995.
3. "Rapitool " - Thierry Dormal, CRIF, TRA sessions,
4* EUROPEAN Coherence ON RAPID PROTOTYPING AND MANUFACTURING
Belgirate, Lake Maggiore, Italy, 1th-1th July 1995
4. “Des moules d'injection pas comme les autres" - Thierry Dormal, CRIF, Rapid Prototyping Conference, Paris, France, 4-5 October 1995.
5. “Le prototypage rapide en 94: du modèle vers l'outil et le prototype technique"- Umberto Baraldi, CRIF, Revue de Fabrimétal 6/94
6, "Réalisation d'outillage prototypes pour l'injection des thermoplastiques"- Baraldi & Emmerechts, CRIF, 2èmes Assises Européennes du prototypage rapide. Paris 04/93 AFPR
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10. "Du modèle vers l'outil de production: l'apport des techniques de prototypage"- Baraldi, Crif, Study days of Crif/Groupe Mécanique de Fabrimétal, Crif Liège, 21/3/95
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12. “La techniques de fabrication de moules d’injection basées sur les RPT" - Baraldi CRIF - Journée de formation de l’ALUEF « Le prototypage rapide et les techniques de production actuelles »- 20/6/95
CRIF Liège
13. “Injection Moulding with soft tooling techniques” - Baraldi -Crif - SME's International Plastics Design &Processing conference - Düsseldorf - 4/10/95

PATENTS

1. patent Application GB 9504995 11/03/95: ZENECA plc ; Stereolithography/resin composition
2. Patent Application GB 9504996 11/03/95: ZENECA plc ; Stereolithography/resin composition
3. Patent Application GB: ZENECA plc ; Filled Stereolithography/resin composition

APPENDIX 2

COURSES AND CONFERENCES ATTENDED

1. "INJECTION MOULDING"
   - CRIF, 30* April, 1993

2. "RADIATION CURING: UV LIGHT AND EB TECHNOLOGY"
   - CPA Intensive short course, Amsterdam, 11-13* October 1993

3. 2nd EUROPEAN CONFERENCE ON RAPID PROTOTYPING AND MANUFACTURING
   - University of Nottingham, UK, 15*-16* July 1993

4. 3rd EUROPEAN CONFERENCE ON RAPID PROTOTYPING AND MANUFACTURING
   - University of Nottingham, UK, 1th-1th July 1994

5. 4th EUROPEAN CONFERENCE ON RAPID PROTOTYPING AND MANUFACTURING
   - Hotel Villa Carlotta, Belgirate, Lake Maggiore, Italy, 1*-1* July 1995

6. 4th EUROPEAN CONFERENCE ON RAPID PROTOTYPING
   - Cité des Sciences, Paris, France, 4-5 october 1995