ICAS-92-6.8.3

RAPID WIND TUNNEL PROTOTYPE USING STEREOLITHOGRAPHY AND EQUIVALENT TECHNOLOGIES

R.Jamieson, Cranfield Institute of Technology,
D.Ae.Sc., Cranfield, Bedford, UK.
and
J.Hammond, British Aerospace, Airbus Division,
Bristol, UK.

ABSTRACT

Stereolithography (SLA) is the name given to a process whereby a lazer beam of ultra violet light is guided into a bath of u-v light sensitive liquid acrylic. Where the light strikes, a process of photopolymerisation solidifies the liquid to a given depth. In this manner a solidified 'slice' of a 3D object can be produced. Successive slices can be cured until a 3D object is 'grown'.

Part 1 of this paper discusses the initial investigation into the feasibility of using SLA as a valid production process for wind tunnel models. The need for good quality (CAD) models is discussed and reference will be made to the rules imposed on CAD modeling together with an overview of how improvements can be made.

Part 2 discusses the follow up stage whereby four competing systems produced a winglet. A brief overview of the process will be given together with charts of comparative accuracy. Finally the conclusions will sum up the feasibility of using SLA in future wind tunnel modelling.

PART 1: REPORT ON WORK CARRIED OUT BY RON JAMIESON FOR B.Ae FILTON (Nov 90 - July 91)

The purpose of this work was to examine the new technology of rapid prototyping (RP) and its impact on time, accuracy and cost when used for the production of wind tunnel models. In this study a 1/14.4 scale model of a proposed wingtip was used as a prototype. The work involved four separate stages:

Stage 1:-	Transfer of CAD model data
Stage 2:-	Production of an STL file
Stage 3:-	Production of an acrylic model
Stage 4:-	Production of aluminium and steel castings.

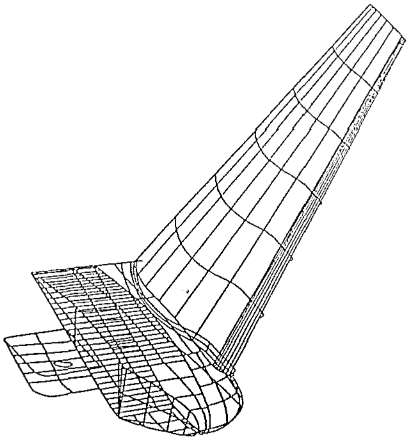

Fig.1

Stage 1:

An IGES file was supplied by B.Ae Filton which described the surface geometry of a winglet. This was read by the Unigraphics (UG) IGES translator using default settings. It was found that simple 'ruled' surfaces produced a fault resulting in their ommission from the UG file. However, the more complex 'sculptured' surfaces which described the aerofoil geometry came through with no apparent problems. A second tape was sent and read with the same results. After discussion with John Hammond of B.Ae. it was decided to continue with the data already read since all of the important data had transferred and the 'ruled' surfaces which were in any case planar could be easily generated in UG. This was achieved using a drawing supplied by B.Ae. and ensuring that the edge curves of the existing surfaces where used as boundary curves for the new surfaces. Ruled surfaces were also used to close off any surface gaps such as that formed by the wing trailing edges. Stage 1 was then complete

Stage 2:

The Stereolithographic Apparatus (SLA) requires a file which describes the outer profile of a given model in terms of faceted triangles (tessellation), this is achieved by listing the cartesian coordinates of the corner points in a set order. This file is referred to as an STL file and is the interface between the CAD system and most of the RP systems. The technology is well documented; see reference list, and this report will concentrate solely on the rules imposed on CAD interfaces for the production of STL files. At this stage what is important is the quality of the SLA interface algorithm offered by a particular CAD vendor. In this study Unigraphics which can handle both surface and solid models, offers a well documented easy to use interface.

The UG SLA interface requires that a couple of parameters are set which will determine the accuracy of the model. These are:

a) Triangular tolerance
b) Adjacency tolerance.

Triangular tolerance determines how close the facets approximate the surface while Adjacency tolerance allows the system to determine if two surfaces are attached (note! adjacency tolerance is not required when using solid models). In addition and to ensure that the SLA rule which requires that all models reside in positive cartesian space and that the Z axis is vertical, the UG SLA interface checks for these conditions and advises on them.

Problems Encountered

The model was placed in positive space, the default settings for triangular and adjacency were accepted and the SLA algorithm was run. The early attempts all failed because:

a) The model was not completely closed;
b) The adjacency tolerance was violated;
c) More than two surfaces shared a common edge.

Solution

Closing the model was simply a matter of examining the model while zooming, rotating and testing for existing surfaces. Gaps such as that along the trailing edge which might not matter when generating N.C. tool paths, had to be closed for SLA interface.

While zooming it became apparent that many of the surfaces had distorted edges and did not actually meet. This explained why the adjacency tolerance was violated. Discussions with John Hammond led to the conclusion that as the anvil 4000 CAD system used by B.Ae. is single precision, the distortions probably take place during the IGES translation. The solution was to rebuild adjacent surfaces so that they used a common edge spline; adjacency was then assured.

The new surfaces were created on separate layers and subsequently tested for accuracy against the algorithm supplied in the UG system. In this manner accuracies of the order of .02mm were maintained.

The third fault; which is a surface model limitation, was caused by breaching the rule which states that no more than two surfaces can share a common edge with another surface. The top wing surface broke this rule and the solution was to break down the long fillet surface into two parts. This rule needs to be borne in mind when designing future parts for RP systems since re-work can take time and accuracy can be lost.

Settings

The model now successfully ran and all that remained was to select a sufficiently accurate triangular tolerance to ensure that a practical limit of 30,000 facets was not exceeded. On advice from 3D systems the model was split into four components each of which could use 30,000 facets and thereby offering increased accuracy. This was done with the tolerances set at:

Triangular tolerance = .05mm
Adjacency tolerance = .05mm

The output file size suggested that the wing stump file contained 31,000 facets using the above settings. The output files were simply appended using a DOS routine at 3D systems. Experiments with the adjacency tolerance showed that while this did not affect the file size i.e. number of facets, it could confuse the system regarding which surface was adjacent to which.

Supports

Production of parts using the 3D systems version of RP require supports underneath the part and on any overhanging parts which protrude more than about 3mm (see Fig 2). The supports are generated in a thin honeycombed fashion which are easy to remove after production.

As shown in Fig. 2, the winglet was produced with the tip surface vertical. This was to ensure that no deviation due to bending under its own weight was induced during manufacture. A support could have been used but this would have resulted in some 'finishing' which would affect the aerofoil surface. The support under the winglet was generated using the underside surfaces and creating a pillar.

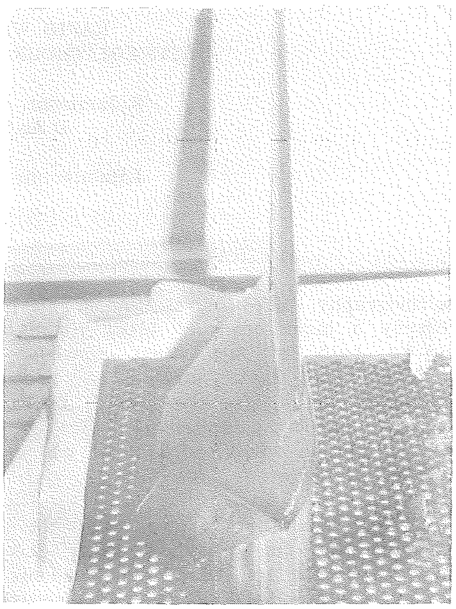

Fig. 2

Stage 3:

Four parts and one support STL files were delivered to 3D systems. These were read into the SLA system and examined on a high quality graphics workstation. The parts assembled and the slicing and weaving algorithms all ran smoothly. Two winglet parts were produced in .25mm slices which took approximately 40 hours. This was due to the length of the support, the volume of the parts and the action of the process. Fig 3 shows one winglet still attached to its support and the baseplate. The layer deposition is clearly visible prior to curing as is the faceted effect on the wing stub. After production the parts are about 98% solid and stable. The curing oven cures the remaining 'entrapped' resin before the part is ready for finishing. Finishing involves removal of excess polymer, removal of supports and light sanding. The process can take a few hours and is a necessary part of this type of RP technology.

In addition the curing oven offers an unwanted source of deformation as observed along the winglet trailing edge were the section is thin. Since curing involves both heat and soak time it must be concluded that a form of stress relieving has taken place.

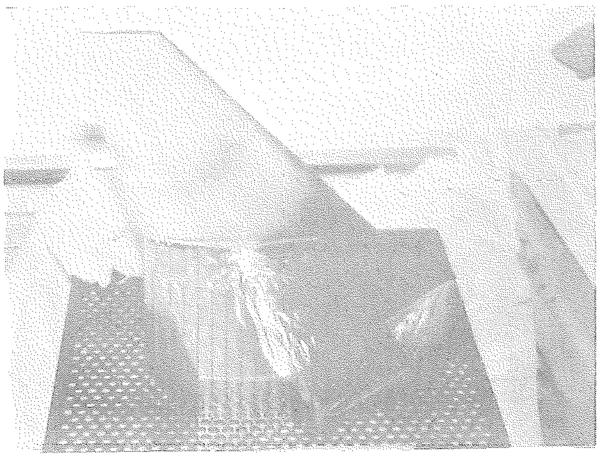

Fig. 3

The parts as cured were quite robust, one was taken by John Hammond for conformity analysis while the second was retained for use in Stage 4.

Stage 4:

Although the acrylic models are rigid and the latest materials are tough, they were not considered suitable for direct use in the low speed wind tunnel. The acrylic model was used as a master for both high and low speed wind tunnel testing.

The lost wax method of casting seemed to offer a rapid and convenient way of obtaining metal winglets with hopefully the RP acrylic substituting for wax. Unfortunately whereas wax melts readily when purged with steam, acrylic requires a higher temperature and explands by about 1% before melting. This has resulted in moulds breaking and the attempts are well documented in Ref. 2. For this study then, we were left with the following procedure:

a) Use the RP model to manufacture a rubber mould;
b) Use the rubber mould to produce an epoxy resin master;
c) Use the epoxy master to produce an epoxy mould;
d) Use the epoxy mould to inject wax;
e) Dip wax in ceramic slurry;
f) Burn out wax;
g) Cast winglet.

Steps b) and c) were precautionary since the casting company; Sterling Metals, had no previous experience of handling acrylic models produced by RP and preferred instead to produce an epoxy master which they were used to dealing with. The epoxy master and moulds were made by a commercially available system. The specification of the silicon rubber, epoxy system and wax are contained in appendices B, C and D.

Casting was achieved using both the low pressure and gravity die casting methods with myself and John Hammond in attendance. The low pressure casting burst its runners during the pour and was scrapped. The cast parts included one .025mm oversize aluminium example. This was achieved by use of a gasket on the mould joints producing an oversized was master. Two aluminium and two steel winglets were cast and taken by John Hammond for dimensional analysis at B.Ae. Filton. See Fig.4.

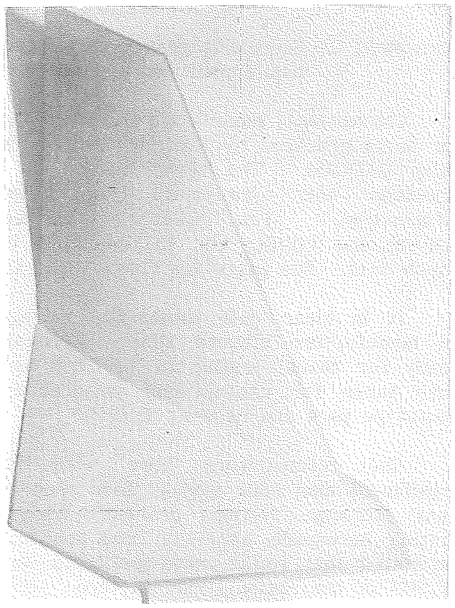

Fig. 4

PART 2: FURTHER DEVELOPMENTS -

Rapid Prototypes Used in Wind Tunnel Tests Conducted by British Aerospace Airbus Ltd. Filton

Using the experience gained from the first prototype model, components were designed and manufactured for tunnel testing using the rapid prototyping process.

Winglets

It was noted that the plastic copy produced by the casting company had fairly good physical properties as well as a very low shrinkage factor. It was decided that from the promising results of the first prototype, the next winglet design which required wind tunnel testing would be made by the Stereolithography process (SLA-250 3D Systems machine at B.Ae. Kingston) and a hard plastic copy made for the test. The mechanical properties of the filled epoxy resin system EPO 999 are shown below in Figure 5. The resin was obtained from Mason Chemical Company Ltd., U.K.

Hardness	**90-95 Shore D**
Compressive Strength	**100-110 N/mm ^{2}**
Tensile Strength	**55-60 N/mm ^{2}**
Elastic Modulus	**8500 N/mm ^{2}**
Density	**1.9-2.0 gm/cm ^{3}**
Max Casting Thickness	**30-40 mm**
Linear Contraction	**0.0005 mm/mm**

Fig. 5

From predicted loads at the required test conditions, Mach number 0.25 and pressure 3.0 bar, it was determined by calculation that the usual safety factor of 4 on ultimate tensile strength would not be met. Since the major cost of the EPO 999 copy is the mould, three pairs of winglets were made, two of which were destructively tested. These tests confirmed that a safety factor of at least 2.5 existed and for proof loaded parts this was considered satisfactory.

The components were made, inspected and tested in the 5m wind tunnel at the Defence Research Agency, Farnborough, to a satisfactory conclusion. The time scale for this work was 1 week for the Stereolithography winglet and a further 1 week for the first EPO 999 copy.

After the first test, the resin manufacturers informed us that the resin was to be superseded by BIRESIN G30 which maintained mechanical properties but improved ease of preparation. This new resin has been used and tested in tunnel conditions similar to the first test.

Leading Edge Research

After the rapid prototype winglet success, another series of tests were selected for component manufacture using rapid prototype technology. Existing low and high speed models were to have their leading edges modified by a variety of profiles.

At the Second International Conference of Rapid Prototyping, 3D Systems announced a new Ciba-Giegy resin XB5143. This resin was not as brittle as the former resins and offered a tougher more flexible product. This resin had just become available in the U.K. when the leading edge tests were first considered.

Model component design was based on the knowledge that the intricate 3 dimensional shapes could be made on a 3D Systems SLA-250 machine with the new XB5143 resin. This would allow any distortions in the rapid prototype during manufacture to be removed as the leading edge components were physically held against the accurately machined metal model wings and bonded with adhesive in position. Previous resins were too brittle and any slight distortion would probably have caused the parts to break when firmly held in position.

Typical components manufactured are shown in photograph, Figure 6.

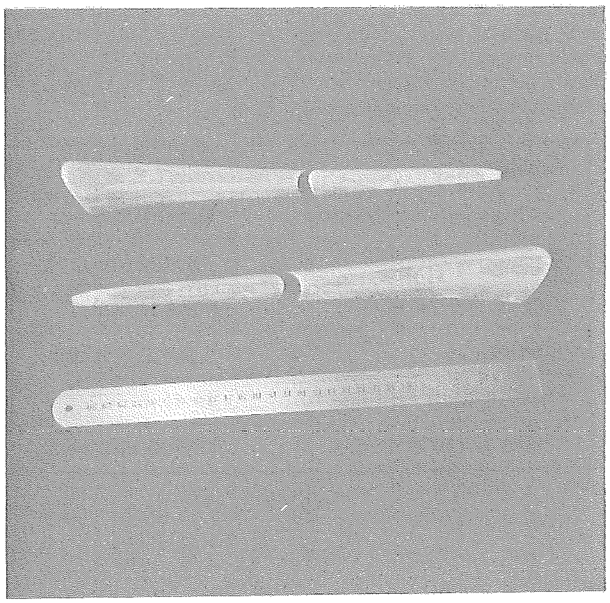

Fig. 6

The leading edge profiles were inspected after clamping against a rigid support and found to lie within -0.17 + 0.15 mm of nominal geometry before hand finishing. The components were located on the model wings using Numerically Controlled machined templates. After the initial attempt it was clear suitable recesses should be incorporated for adhesion, improving the final fitting. A wide variety of leading edge profiles were investigated using rapid prototyping technology which were produced at a local bureau, Formation Engineering Ltd. U.K. After initial IGES transfer problems were addressed the elapsed time for production of these parts was about 1 week. The best time achieved was delivery of parts 3 days after receipt of a satisfactory tape of IGES data.

Timescale and Cost Comparison Between Rapid Prototypes and Conventional Methods

The major advantage of reduced elapsed times offered by rapid prototype technology can be lost when using bureau services or other departments outside of ones control without careful preparation. Data transfer between different CAD systems using IGES has its problems and tape cartridges between different workstations are surprisingly incompatible. Once technical problems have been sorted, the buying office must be geared up to rapid response. From receipt of an urgent quotation, at least an order number will be required within three days, or the part could be made and not delivered. Rapid delivery to the site where the model is being tested also requires that arrangements are made to ensure that parts are not delivered to Goods Inwards but delivered direct, according to set instructions.

Figure 7 shows comparison between times for conventional and rapid prototype manufacture. The times are examples from actual part manufacture. The rapid prototype times are for parts made at a local bureau and an outside department after potential problems from using bureau services had been addressed.

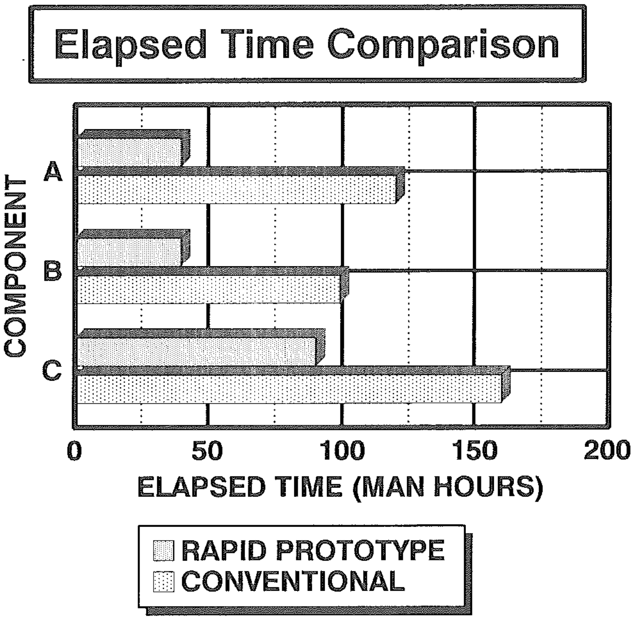

Fig. 7

Component A - Stereolithography part used direct.

Component B - Stereolithography part used direct.

Component C - Stereolithography part manufacture, mould produced and epoxy resin copy cast.

Conventional manufacture used in the comparison is for parts produced by Numeric Control (NC) programming using CADCAM. The times include the preparation of drawings and appropriate jig, billet and set-up information. The billet is blocked down using conventional milling and NC machined using rough and finish cuts. The parts are finally hand finished.

It is clear that substantial savings can be made on manufacture elapsed time. Critical items can be ready for tunnel testing in as little as a third of the time taken for conventional manufacture if the rapid prototype part can be used directly.

Cost comparisons have been favourable since significant man hour savings have been made. After the data exchange systems problems were sorted between British Aerospace at Filton and the local bureau it is estimated that rapid prototype costs were of the order of 30% of conventional manufacture.

The timescales quoted so far have been for rapid prototypes produced from sites within the U.K. A bureau service using a Cubital machine situated in the U.S.A. has also been used. The distance involved however produced difficulties in communication and a very slow response (4 weeks). Only local services are therefore considered for project work, the parts produced by Cubital however were used for system evaluation, the findings are included in this report.

Rapid Prototype Systems

The first rapid prototype machine available on the market was the SLA-250 by 3D Systems. The vast majority of rapid prototype machines in use today are 3D Systems machines. There are however a significant number of new systems being developed, a number of which are on the market or not far from it. The total number of systems is twenty four at the last count. There follows a brief description of some of these systems. The systems selected for more detailed description are either available on the market or not far from it and have been considered for producing wind tunnel model parts.

Categories

There are numerous ways to categorise rapid prototype techniques. One method is to categorise from the state of the raw materials. (1)

Liquid

Power

Solid

Liquid

(i) Solidification of a liquid polymer by photopolymerisation. This technique is applied by the following methods:-

Laser beam	Lamps (optical mask)	Holography
3D Systems EOS Quadrax Grapp Du Pont Laser Fare Sony/D-Mec Mitsui Mitsubishi/CMET	Cubital Light Sculpting	Quadtec

(ii) Melting and solidification. This technique is the basis of the following systems:-

Fused deposition manufacturing	**Shape melting**	**Ballistic particle manufacturing**
Stratasys	Babcock & Wilcox	Perception Systems
Perception Systems	Jero	Automated Dynamics Co.

Powder

(i) Selected Laser Sintering. Sintering is the process of applying heat to a layer of powdered material with thermoplastic properties so that the powder becomes viscous and quickly solidifies. This technique is the basis of the following systems:-

DTM
Hydronetics
Westinghouse

(ii) 3D Printing. Grains of powder are bonded together by selectively adding a glue. This process has been developed by MIT.

Solids

(i) Laminated object manufacture. Thin sheets of a variety of materials are cut and glued together. This process has been developed by Helisys, formerly Hydronetics.

(ii) Foils of semi-polymerised plastic are bonded together by further photo-polymerisation. This process has been developed by Grapp.

Systems Considered for Wind Tunnel Model Component Manufacture

Four systems have been considered for manufacture of model components, 3D Systems, EOS, Cubital and DTM. There are three methods used by these systems.

3D Systems and EOS

The technology used by 3D Systems is the solidification of a photo-sensitive liquid polymer using an Ultra-Violet laser beam. A platform is positioned in a vat of liquid polymer just below the liquid surface. An elevator positions the platform accurately to a predetermined depth, typically 0.1mm (see Figure 8).

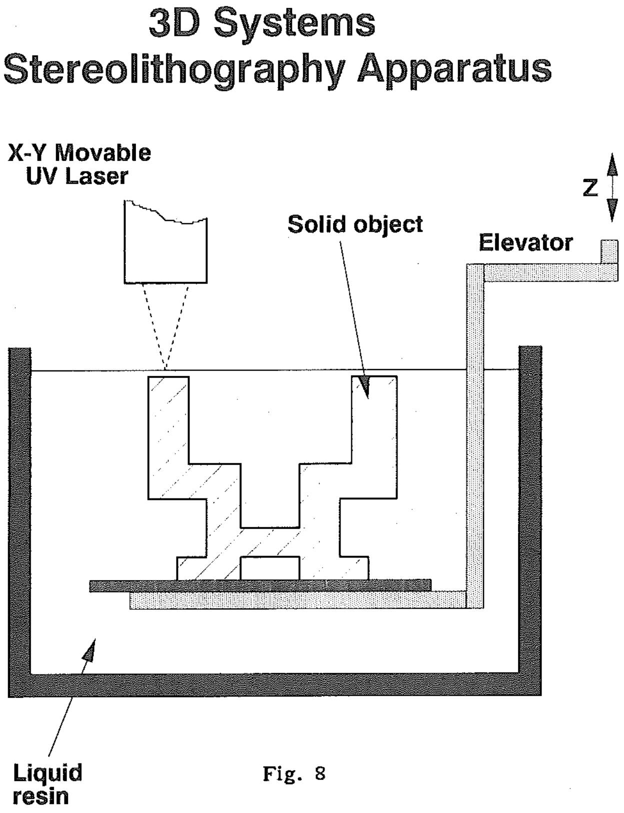

Fig. 8

A laser beam scans the liquid surface, solidifying the polymer in a series of points called voxels (see Figure 9).

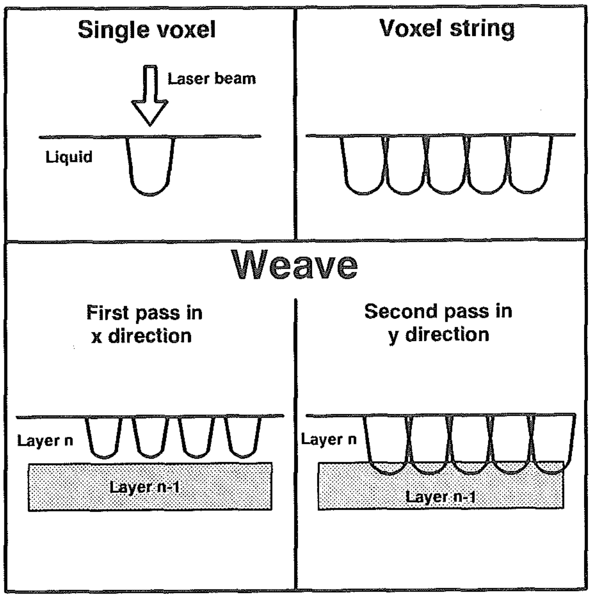

Fig. 9

The voxels are large enough to overlap and form a continuous string. The laser traces out the shape of the first cross sectional slice of the part to be manufactured in full. When complete, the elevator lowers the platform another 0.1mm for example, and a wiper moves across the liquid surface to level it. The next layer is traced, starting with the internal and external profiles, then filling in with a cross hatching known as "weave". This method has been developed to reduce problems associated with shrinkage which occurs as the polymer solidifies. The cross hatching in the first direction does not penetrate the layer below allowing free shrinkage. The cross hatching in the second direction penetrates more deeply fixing the layers together.

The laser traces further layers in a similar fashion until the last layer which is completely solidified. The elevator is raised to lift the part out of the vat.

The part is at this stage not fully cured. Some liquid polymer, of the order of 2% by volume is captured in the part and the part is in a "green" state. Full curing is carried out in a post curing UV oven for speed although normal daylight will suffice.

3D Systems manufacture 3 machines with different vat sizes.

SLA-190 Part size 190 x 190 x 250 mm
SLA-250 Part size 254 x 254 x 254 mm
SLA-500 Part size 508 x 508 x 610 mm

EOS machines also solidify photopolymers in layers using a UV laser. There are currently two machines available.

Stereos 400-25 Part size 400 x 400 x 250 mm
Stereos 400-60 Part size 400 x 400 x 600 mm

<u>Cubital</u>

The Cubital machine utilises photopolymers but differs from the former processes by the manner in which the photopolymer is exposed to UV light (see Fig. (10). (2)

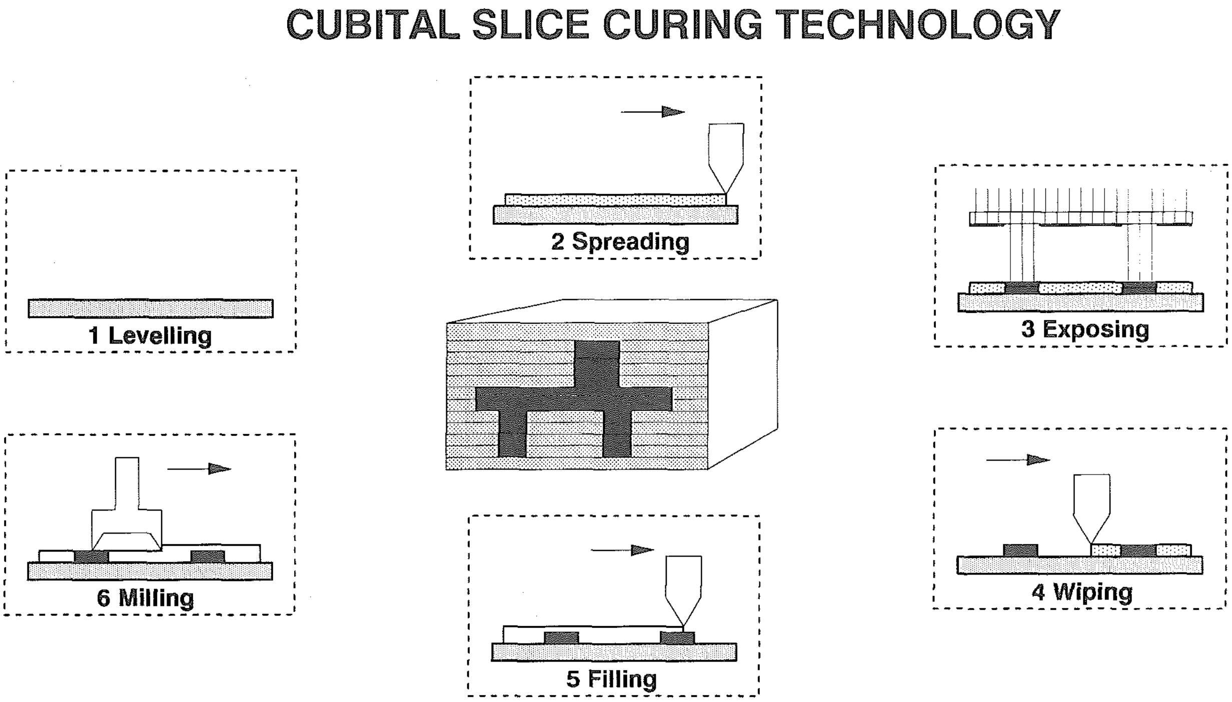

Fig. 10

A thin layer of liquid resin is spread on a platform to a predetermined depth (0.05 to 0.15 mm). The layer is exposed to a strong flash of UV light through a mask. The optical mask is prepared by charging a clear glass plate through an "image wise" ionographic process and developing the charged image with electrostatic toner. A fresh mask is prepared for each layer by physically wiping the mask plate and recharging the plate for the next layer. The exposed area of the photopolymer solidifies and the excess unsolidified liquid resin is wiped clear.

The platform is passed under a wax applicator where melted wax is spread over the surface, filling the voids left where the liquid resin was wiped clear. The wax is cooled by pressing a cooling plate down onto the melted wax and the top surface is skimmed with a milling disc to the specified thickness. The platform is lowered by the thickness of one layer and liquid resin applied to the surface again, in readiness to repeat the process.

When complete, the solid resin part is encapsulated in supporting wax and is extracted by melting the wax away.

The Cubital machine is named the Solider 5600. Maximum part size is 480 x 330 x 500 mm.

DTM

This system uses selective laser sintering technology. A thin layer of powder is spread by a roller across the top of a piston in a cylinder which is positioned at a predetermined depth (see Figure 11).

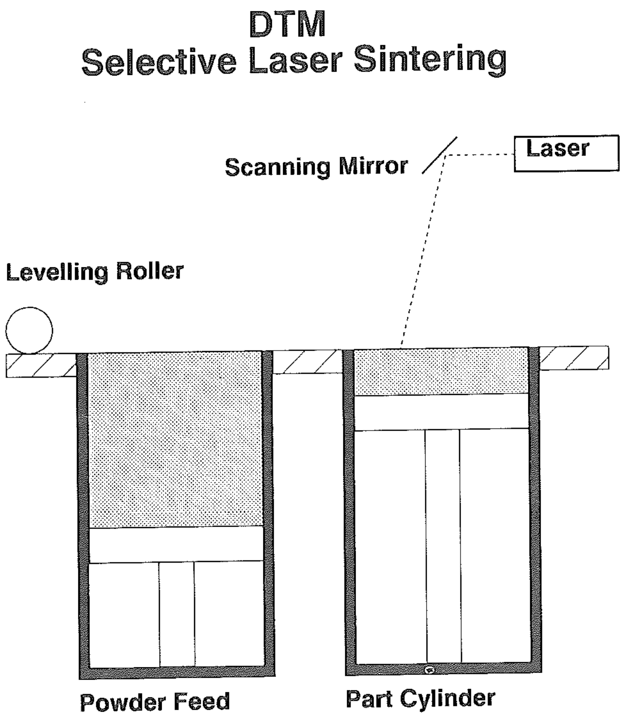

Fig. 11

The powder is heated to a temperature just below the melting point of the particular powder being used. The powder is raster-scanned with a modulated laser beam whose intensity is controlled in accordance with information from the CAD data. The laser intensity is high where the cross section is solid causing the powder to fuse. The remaining powder is unaffected and acts as a support. When the first section is complete the platform is lowered and fresh powder is delivered. This is supplied from a second cylinder which stores powder and is displaced by the action of a piston. The roller spreads the powder evenly as before and the process repeated.

Several materials have been successfully sintered and are currently available. These are PVC, polycarbonates nylon and investment casting waxes. Ongoing research into other materials includes a variety of ceramics, metals and composites. There is little information available on the success of these materials.

The machine developed is the SLS Model 125 with a maximum part size of 305 mm diameter x 381 mm high.

Inspection Results

Co-ordinate measuring machine inspection was carried out on parts made by three of the aforementioned systems. No parts have been made for British Aerospace at Filton by DTM. During inspection it was found that any distortion on the flat faces used for datums could cause significant errors to be recorded, which did not reflect the overall part accuracy. To overcome this, three points were selected on the surface of the parts which represented the important overall dimensions. An optimisation process was used to modify the datum position to produce the best fit of those three points, effectively optimising the part in 3D space.

An important aerodynamic consideration was the accuracy of the section profile. In addition to the overall accuracy, an individual profile was inspected and optimised by isolating it and arranging it to achieve the best comparison with the CAD definition. This highlighted the accuracy.

The first prototype winglet was made on a 3D Systems SLA-250 machine and some time later a duplicate part made on an EOS Stereos 400-25. The inspection results of the overall accuracy and an optimised section are shown in Figures 12 and 13.

As previously described, a second winglet was made on a 3D Systems SLA-250 machine (and an epoxy resin copy wind tunnel tested). The same part was made on a Cubital Solider 5600 and the inspection results of overall accuracy and an optimised section are shown in Figures 14 and 15.

Comments on Results

First Prototype Winglet

To give an indication of part size, the component outside dimensions are 240 x 162 x 108 mm.

The overall accuracy of the first 3D Systems part is not very good. This is believed to be due to the crude support during post curing causing the most significant distortion. The part errors range from -0.717 mm to +1.648 mm maximum. The isolated fit of an individual section shows a much better result of -0.080 mm to +0.0916 mm. This is a measure of the laser accuracy as the part was built with the winglet vertical.

The overall accuracy of the EOS part is best with material errors in the range -0.800 mm to +0.455 mm. The result of the isolated fit of an individual section are not as accurate as the 3D Systems part but the part was built in a different orientation. The EOS part was built with the winglet flat so that the profile was built in layers, the build of the section is therefore cruder. The isolated fit inspection ranges from -0.086 mm to 0.225 mm.

Second Winglet

The second winglet produced by rapid prototype methods has outside dimensions of 163 x 130 x 111 mm.

The accuracy of the second winglet produced on a 3D Systems machine is better. Overall accuracy ranges from -0.994 mm to +0.834 mm. The isolated section accuracy ranges from -0.178 to +0.264 mm. This part does not meet the standards required. (A resin copy was used for a wind tunnel test after further hand finishing and setting adjustments had been made to improve accuracy).

This winglet was also produced on a Cubital Solider machine. The inspection results show overall accuracy ranging from -1.094 mm to +1.100 mm and the isolated section range from -0.230 mm to +0.416 mm.

Systems Comparisons

3D Systems

Advantages

This 3D System machines are by far the most widely used and therefore this technology has the greatest user experience. · Extensive accuracy checks have been published by users and it is logical to assume that user feedback will assist in identifying major issues.

An SLA-250 machine produced a second winglet part accurately enough for wind tunnel tests. 3D Systems are continuing research on problems such as shrinkage, swelling, cantilever curl distortion, post cure distortion and creep (3).

The machines can be left unattended as the parts are built.

There is little waste during the process, unsolidified resin is reusable.

The company also appears to have the safest patent on this technology.

Disadvantages

Overhangs required on manufactured parts will cause the cured slices to float away unless restrained by supports. It is therefore necessary to add supports to the CAD model although there is software available

Parts are not generally used for investment casting directly as expansion causes the ceramic mould to crack. A few casting companies however have been successful and offer this service. Research is in progress for resins which can be easily used for investment casting.

Parts must be post cured to fully solidify resin.

EOS

Advantages

The technology used by this system is similar to 3D Systems and has the same technical merits, there is little waste and the machine can be left unattended.

The company is researching the possibility of laser inspection of the manufactured parts on the machine which would reduce considerable effort on part inspection. It might even be possible for a system to redefine the computer model and rebuild the part with greater accuracy.

Disadvantages

CAD models require supports for overhangs.

Parts not generally used directly for investment casting.

System is new to the market and has yet to establish user base.

Parts must be post cured to fully solidify resin.

Cubital

Advantages

No supports are required as the model is supported in wax.

The wax used for supports can be used directly for investment casting. Hence by producing a CAD model of a part with an outer skin, the machine can produce a part which encapsulates a wax part in a thin layer of solidified resin. The skin can be removed and the part used directly for investment casting. Wind tunnel model components usually require thin trailing edges however and removing the thin outer skin of resin is not practical without breaking the internal wax. Research is in progress to provide a resin which can be used directly for investment casting.

No post curing is required, eliminating a potential source of distortion.

Disadvantages

The machine utilises a high number of moving parts during each cycle offering a higher potential for problems. For example, the surface finish of a part produced on this machine relies on the optical mask having sharply defined edges and being precisely relocated after each wiping process.

The process has a high wastage of resin, wax and toner.

Machine size is large.

I believe an operator should be in attendance during operation. The process is more operator intensive as more consumables have to be loaded and waste products removed.

Only a limited user base established to date.

DTM

Advantages

No supports are required as the model is supported by powder.

Investment casting waxes can be used directly.

No post curing is required, eliminating a potential source of distortion.

If research can overcome significant problems and enhance the process to safely, reliably and accurately sinter metals, this would offer a major advantage over competing systems.

The machine can run unattended.

Disadvantages

Although a part has not been made for British Aerospace at Filton to evaluate accuracy, investment casting wax parts made on the system have been examined. The surface texture appeared very coarse and thin edges were poor. The inability to create thin edges would be a problem for wind tunnel model components.

The SLS 125 machine is due to be released to USA market early 1992. It will take some time to establish a user base.

Conclusion

It has been demonstrated that wind tunnel model components can be produced to a standard suitable for testing, in terms of strength and to a lesser extent accuracy, using rapid prototype technology. Where a more flexible resin can be bonded in position to rigid datum components, the accuracy is much more acceptable. Elapsed manufacture time has been achieved in a third of the time taken for conventional manufacture using a bureau service with a 3D System SLA-250 machine. An in-house machine could offer further elapsed time savings.

Rapid prototype technology offers substantial benefits in specific areas of wind tunnel model design. It is hoped that more research in resins could broaden the application of this technology.

References

1. Material Incress Manufacturing By Rapid Prototyping Techniques, Prof. J.P.Kruth.
2. Automated Modeling Machines, Mr. I.Pomerantz.
3. The Present State of Accuracy in Stereolithography, 2nd International Conference on Rapid Prototyping, Mr. J.Richter, Dr. Paul Jacobs.
4. Proceedings from the 'Second International Conference on Rapid Prototyping' June, 1991, Dayton, Ohio, USA.
5. 'Prototype Casting by Stereolithography', W.E.Cromwell, Allied-Signal Aerospace Co.
6. 'Three Dimensional Printing: Ceramic Shells and Cores for Casting and other applications', Emmanuel Sachs, Michael Cima and James Cornie, Massachusetts Institute of Technology.

PARTICIPATING COMPANIES INCLUDE:

A) 3D Systems, Inc., Limited, Unit 7, The Progression Centre, Mark Row, Hemel Hempstead, Herts, HP2 7DW.

B) E.D.S., Wells Court, Albert Drive, Shearwater, Woking.

C) Sterling International Technology Limited, Gipsy Lane, Nuneaton, Warwicks.

D) British Aerospace Commercial Aircraft, Wind Tunnel Department, Filton.

E) D.Ae.S. College of Aeronautics, Cranfield Institute of Technology.

F) Formation Engineering Ltd., Gloucester.

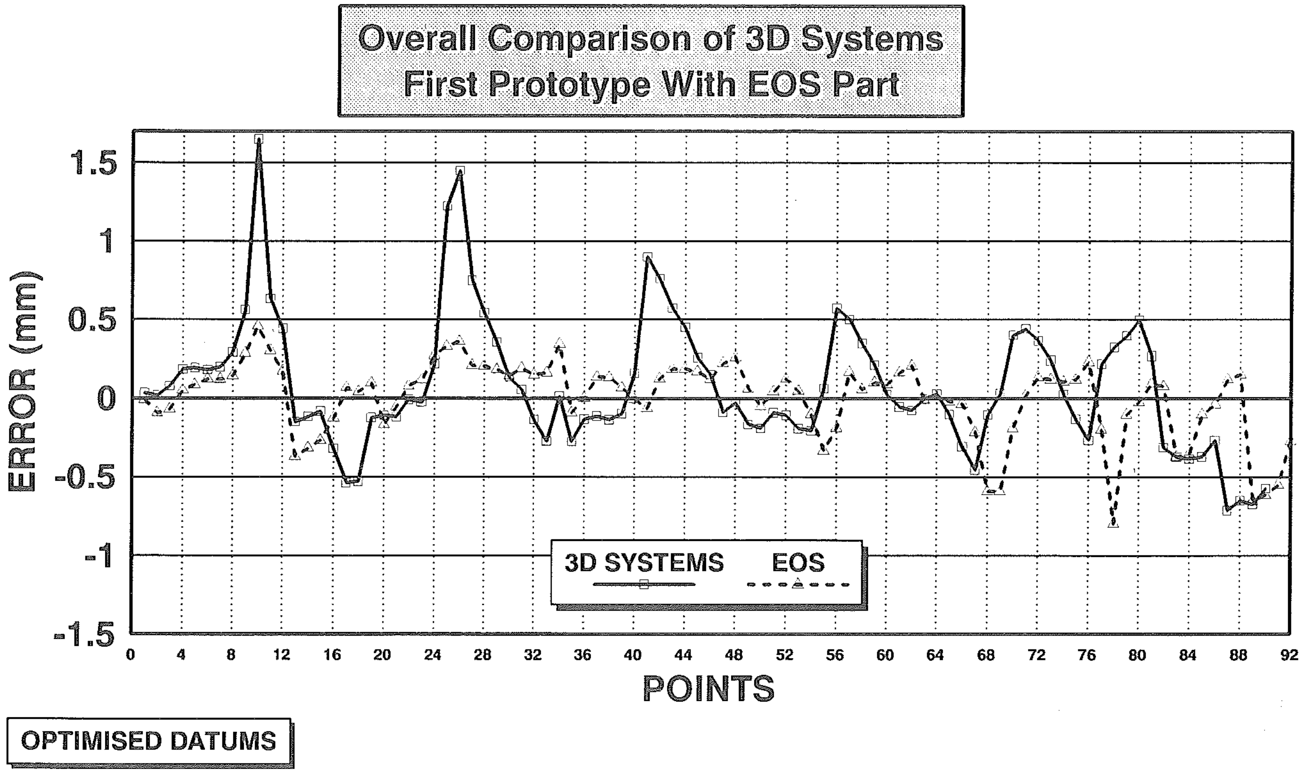
Overall Comparison of 3D Systems
First Prototype With EOS Part
ERROR (mm)
1.5
1
0.5
0
-0.5
-1
-1.5
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
POINTS
3D SYSTEMS
EOS
OPTIMISED DATUMS

Fig. 12

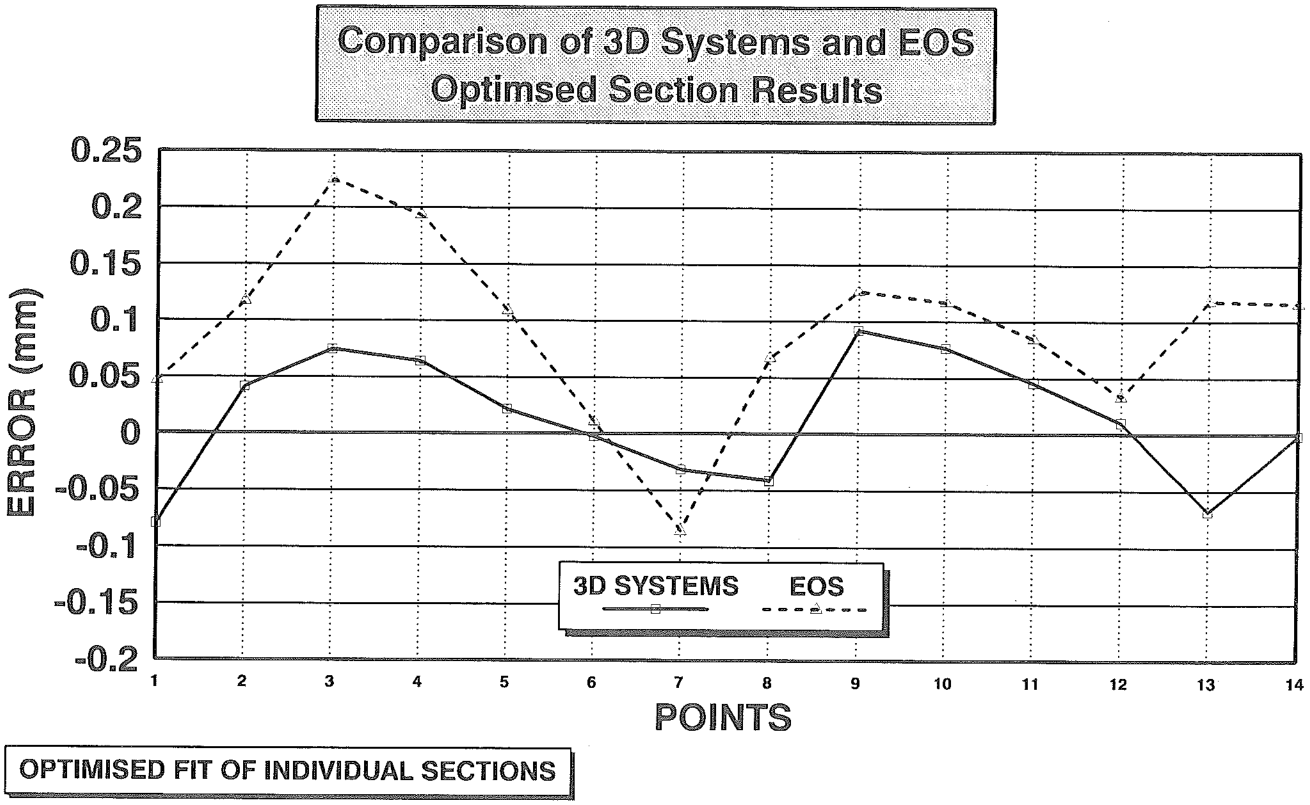
Comparison of 3D Systems and EOS
Optimsed Section Results
ERROR (mm)
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
1
2
3
4
5
6
7
8
9
10
11
12
13
14
POINTS
3D SYSTEMS
EOS
OPTIMISED FIT OF INDIVIDUAL SECTIONS

Fig. 13

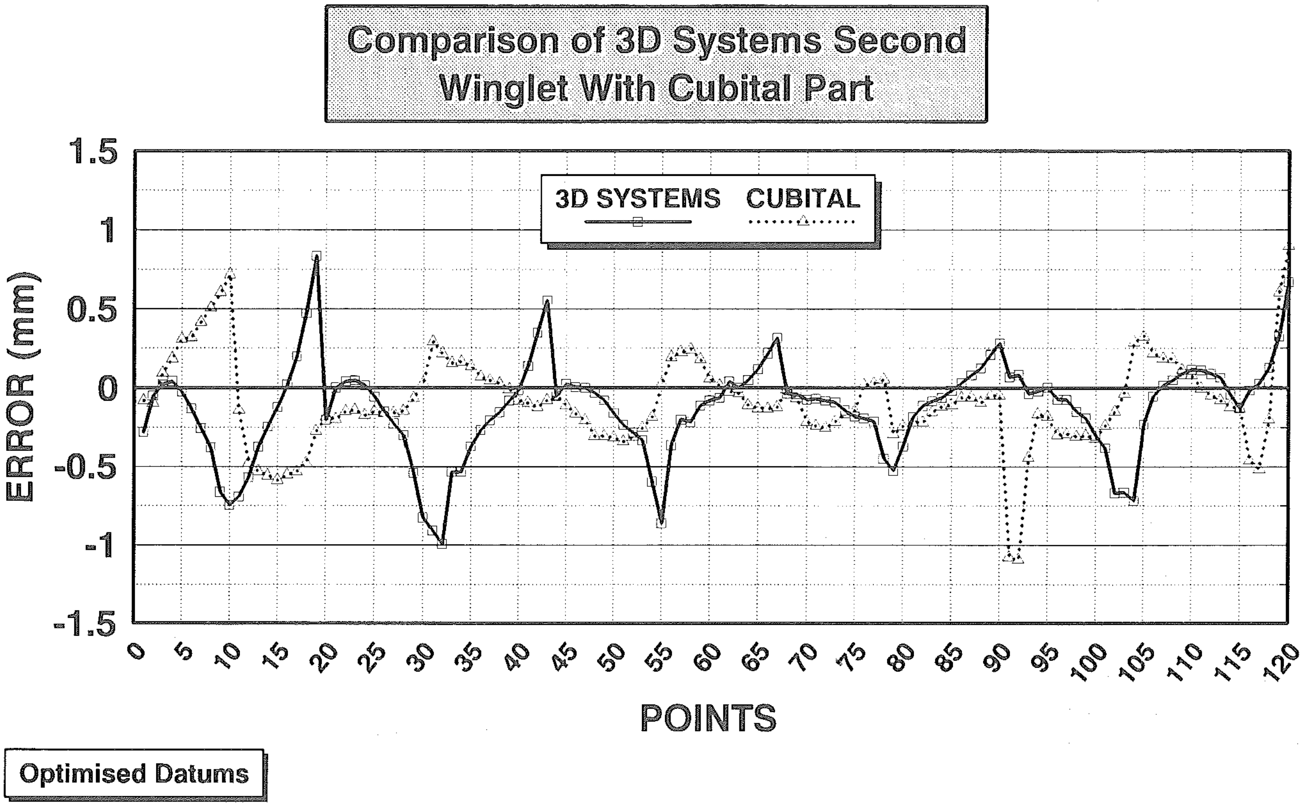
Comparison of 3D Systems Second Winglet With Cubital Part
3D SYSTEMS
CUBITAL
ERROR (mm)
1.5
1
0.5
0
-0.5
-1
-1.5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
POINTS
Optimised Datums

Fig. 14

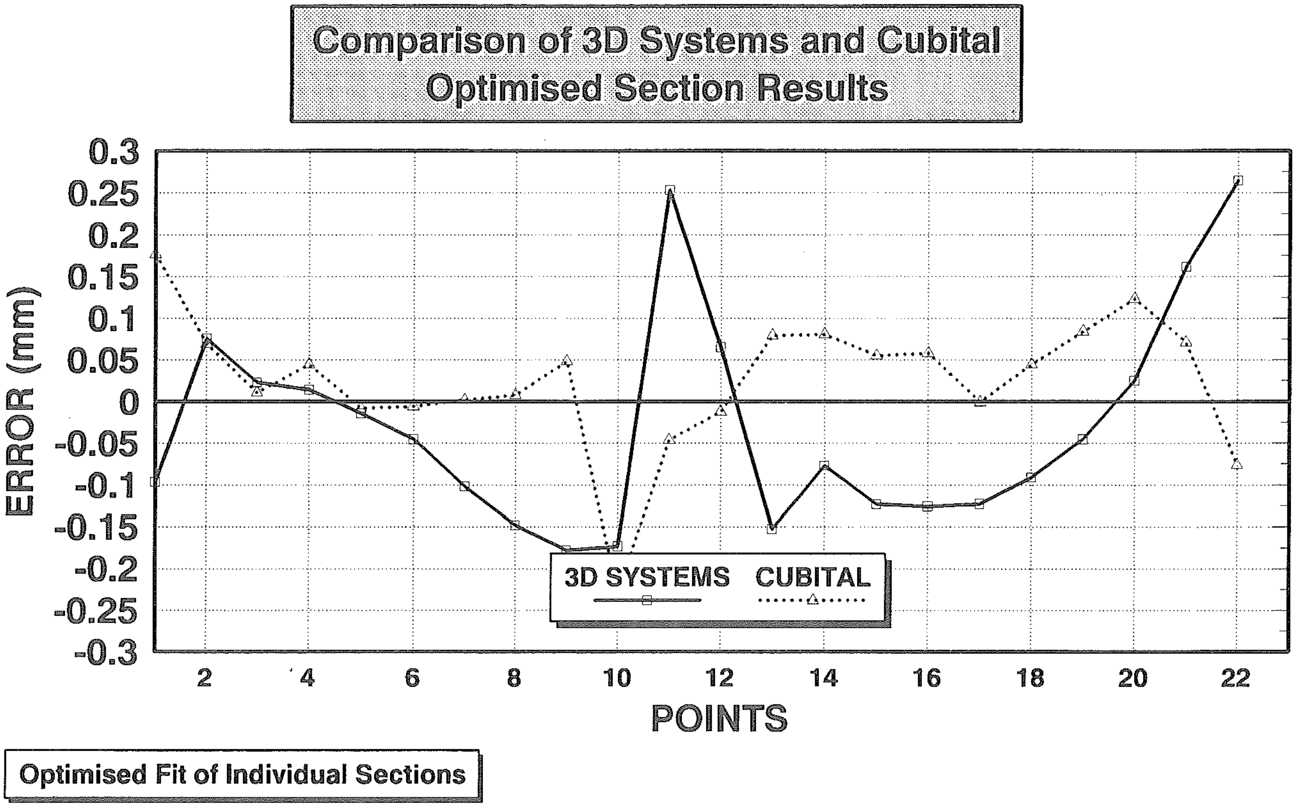
Comparison of 3D Systems and Cubital Optimised Section Results
ERROR (mm)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
3D SYSTEMS
CUBITAL
2
4
6
8
10
12
14
16
18
20
22
POINTS
Optimised Fit of Individual Sections

Fig. 15