STEREOPHOTOLITHOGRAPHY: A BRAND NEW MACHINERY

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I ALTERNATIVE DEVELOPMENT STRATEGIES (1984-1991):

I.1 LASER 3D S.A. (1991-1992).

Stereolithography (SPL) is only one of the new technologies developed originally and simultaneously in FRANCE (CNRS- July 84. French Patent N° 84 11 241) and in the USA (U.V.P- C. HULL Aug. 84 . USA Patent N°45 75 330) to tackle "Rapid Prototyping" (RP) bottlenecks, as well as faster and better design needs (CAD induced).

SPL applications have developed at different speeds in the USA and in EUROPE, due partly to different patent positions, industrial motivations and market demands. Today in EUROPE (June 92), two companies are proposing very similar SPL machinery systems of what we call first generation SPL/L-S (L-S stands for Liquid- Solid), the 3D SLA 250/500 family (1988-92, USA) and EOS STEREOS 400/600 family (summer 1991-1992, GERMANY). A recent article ("Industries&Techniques"-May 92) underlines the obvious similarities between the two first generation systems.

A third company, LASER 3D S.A. entered the RP field in France in 1991, by acquiring all patents and know-how controlled by the original french team (1984-1991). After analysing with american (1990-1991) and european users (1991-92), the technical constraints imposed by the first generation SPL/L-S machines, LASER 3D has designed (March 92) and is putting on the european market in the fall 92 a totally new technical concept (second generation SPL/L-S Sept 92- Appendix 1) the SPL 1000/LSA using for the first time high power UV lasers (1 Watt). L3D marketing strategy is also entirely new and was requested by several "sophisticated" SPL users who are more interested in CAD Design optimization and product development than in expensive first generation SPL machinery operations. LASER 3D will provide experienced operating SPL personnel that the SPL user won't need to have or train. Users can concentrate on what they know best: their product development and CAD design optimization.

I.2 Alternative development strategies (1984-1991):

Two independent researchers started SPL technologies in 1984: Prof. J.C. ANDRE of CNRS-ENSIC in Nancy and Mr. C. HULL of UVP in California. They followed very different R&D development strategies; Mr. HULL put first a SLA 250 machinery in the field and sold it, making technical improvements along the way (1988-92); Pr. ANDRE did not put the machinery in the field: he built first several prototypes to study the most important physical laws controlling SPL applications (1986-91). Then the new SPL 1000/LSA was finally designed in 1992, taking advantage of both 1/ scientific knowledge accumulated from 1988 to 1992 and also, 2/ of a much broader user experience leading to the definition of a simpler more efficient SOFTWARE architecture.

From 1984 to 1992, continuous research was conducted in the CNRS-ENSIC laboratory in Nancy, not only in the SPL-L/S (photopolymerization of liquid resins), but also in SPL-S/S (solid-solid process using solid films) and in SPL-P/S (powder-solid process or sintering).

In SPL-L/S, photopolymerization was studied with UV, visible and IR light; the best results in terms of ACCURACY and SPEED were obtained with UV light.

SPL-S/S (solid-solid technology) is based on the phototransformation of thin films. FIRST FRENCH PATENT was filed in 1986; new work was conducted and new patents were filed later on, extending the process to cover the use of composite materials, including fillers and/or fibers.

In SPL-P/S (powder-solid technologies), research started in the mid 80's. Many different materials were studied. Today, research is concentrating on CERAMIC MATERIALS.

I.3 Prototypes and concrete results:

Several prototypes were built from 1984-1992, to follow technical advances and to exploit concrete experimental results. We shall only list the most important prototypes below:

1988: First fully automatic SPL-L/S machine using already a high power 500 mW Ar. Ion laser.

1989: More efficient machinery, using galvanometric mirrors and a high power 500 mW Ar.Ion laser. Faster scanning speeds were possible. Software architecture was very flexible, thus allowing to study efficiently a very wide range of working parameters. Many PHD students were trained on this machine between 1989 and 1992 (5 years experience with high power UV Ar.Ion laser).

1990: The feasibility of the SPL-S/S process was fully completed; the first SPL COMPOSITE PART was made. This original work was then developed in 1991, in cooperation with DASSAULT AVIATION, and new patents have been filed worldwide. An industrial machinery could be defined by L3D in 1993, allowing hopefully the construction of large SPL structural parts by 1994. One key process variable still needs to be properly managed to make the process very attractive.

1991: A third SPL-L/S prototype was built to prove the industrial potential of a new recoating process, defined earlier. The interesting characteristic of this apparatus is that the RECOATING TIME is totally masked- i.e the laser is creating a solid material WITHOUT INTERRUPTION. For the moment this prototype is still limited to particular part geometries, but it is possible to extend the principle to other geometries.

A new 1991 prototype machinery was designed , to consolidate earlier work done in powder sintering and to extend earlier research into ceramic sintering applications. Ceramic parts are currently made in 1992. Key process variables are still being assessed before defining a real efficient industrial process SPL/P-S.

II L/S TECHNOLOGY: KEY PARAMETERS:

II 1 ACCURACY: importance of resin material

For the Liquid-Solid technology (SPL-L/S) it is very important to work with the proper resin. The problem is to find materials combining several characteristics which are often in opposition (low viscosity and low shrinkage, high reactivity and high conversion degree, etc...). Recent major chemical companies entry in SPL-L/S should (Allied Signal, Grace, Loctite, etc...) make available several new attractive materials with better, more flexible SPL properties. We can hope that industrial materials improvements will accelerate. We will underline below two essential problems, related to resin behaviour, in the Stereolithography process, which are directly linked to the end-product qualities (surface finish, macroscopic accuracy).

II.1.1 Recoating system:

Different recoating systems are working today on several SPL-L/S machines. All of them are leading to liquid surface deformation, and a certain amount of time is needed to obtain complete relaxation of the surface. Experimental work pointed out that the liquid surface deformation is exponentially decreasing with time (see fig.1), relaxation time for a given resin is almost exponentially rising with decreasing layer thickness. Decreasing layer thickness is an objective which controls GOOD SURFACE FINISH.

It is clear that increasing viscosity leads to increasing relaxation times, but resins are not simple rheological materials, and one can sometimes obtain curious results. For example, comparing a 1.2 Pa s acrylate resin, and a 0.6 Pa s epoxy resin, we could observe an inversion point following the relaxation of these two products versus time. Figure 2 shows in fact that in the beginning of the experiment, the lowest viscosity resin (epoxy) is relaxing faster than the acrylate resin, but after this first period, the tendency is inversed. Rheological studies pointed out that the epoxy resin was no Newtonian material (fixed viscosity), but has an increasing viscosity when sterees are decreasing: this explains the surprising observed result.

These two examples are pointing out that the rheological behaviour of resin material is also to be taken into account to define a "good resin" for the Stereolithography process.

II.1.2 Sources of macroscopic deformations:

One of the essential problems in SPL-L/S, is to avoid part deformations due to resin shrinkage. Work has been done to model mathematically this behaviour for a simple part geometry. Figure 3 shows a part composed of two distinct materials: one is non evolutive material (Young modulus E1, thickness e1, no shrinkage), supposed to be simulating the already created layers, the other represents the new layer in formation, having evoluting parameters (Young modulus: E2= 0 to E1, shrinkage S= 0 to fixed arbitrary value, thickness e2). This very simple situation allowed computation of the evolution of the deformation versus time (arbitrary time scale). Figure 4 shows that different final results were obtained (case I, II and III). In fact, different supposed evolutions of E2 versus S, for the same final values of E2 and S, were

simulated. Those different cases are leading to different time evolution of the deformation, but the most interesting result is to point out that the final deformation value is changing.

So it is clear that part macroscopic deformations are **not only related with resin shrinkage** and final mechanical properties, but also depend on the evolution of mechanical parameters during curing. Some resin manufacturers have worked on convergent problems and have designed resin materials with a special curing mode (Rapid Prototyping, Nottingham 6-7 July, pp 163-182), the objectives being to limit the formation of internal stresses during curing.

Figure 5 shows (simulation) that the non isotropic light absorption leads to spontaneous deformations (due to shrinkage). Rheological tests were also performed on the cured material, in particular to study long periods (several months) evolutions (ENTROPIE n°167-1992, pp 51-61).

II.2 INDUSTRIAL CONSTRAINTS:

For a given resin, it is always possible to improve the quality of the parts. For improving **micro-precision**, you "just" have to take the time necessary to reach complete surface relaxation (vertical precision) and to work with a low scanning speed to avoid the inertia problems relative to the beam deflection device (horizontal precision). **Macro-precision** is more difficult to improve, because of the numerous sources of deformations, and because deformations are varying with the geometry of each part: trial-error sequences and users "feeling" are sometimes necessary ingredients to use before reaching the requested accuracy.

The above "pseudo-solutions" are not proper industrial solutions which would like to ultimately reach::

- Low cost manufacturing
- "Press-button" machine and repeatability

We will describe below the industrial solutions adopted in L 3D's new machinery, in terms of:

- **Improving process efficiency**
- **Improving manufacturing speed**
- **Reducing user's training requirements (new software concepts)**
- **Reducing operating costs**

III LASER 3D - SPL 1000 /LSA DESIGN: A NEW STEP IN TECHNOLOGY

As described earlier, the french team used several working prototypes from 1988 to 1992, developing a 5 year-experience with high power Ar Ion UV laser (1988-92), assessing experimentally the importance of all major key variables, before deciding to integrate all the accumulated knowledge (1984-92) into an industrial venture, controlled by LASER 3D S.A. in 1991.The industrial entrepreneur LASER 3D made an extensive study of the SPL/L-S market in the USA in 1990-91, assessing the relative strengths of 3D Systems/ DUPONT /QUADRAX/ LASER FARE first generation technologies, before deciding to buy the french second generation technologies and know-how in order to define a completely new product: the SPL 1000 /LSA,

with a new marketing strategy designed to enter in 1993 the existing market of the "sophisticated SPL" users (100 kg/year potential), whose needs are well defined today (1992).The new second generation SPL 1000 /LSA, based on the liquid-solid technology, was designed in 1992, 1) to take into account the most sophisticated American and European SPL users (above 100 kg / year potential) and 2) to use the french 1984-92 historical work.

We redesigned entirely a new machinery and were forced to solve new problems, keeping in mind two coherent objectives:

- **decrease the process costs**
- **increase technical productivity of each technical function.**

Particular attention was taken to the design of a simple, real industrial working tool which does not necessarily require special knowledge and/or experience (software architecture), in order to facilitate market entry and acceptance of this technology by new "users". In particular, the following new software features are included:

Step 1: STL transition

- Scanning vectors computed during part manufacturing

  ==> Slice + Merge = 0

  No necessity for sliced part memorization

- Pre-processing:
  - Part preparation while the machine is working
  - Possibility to see final aspect of the sliced part before manufacturing
  - Integrated CAD system (if needed), directly related by native format with the manufacturing machine.
  - New concept: "**styles**"

No parameters, but style selection which AUTOMATICALLY chooses priorities imposed by the part designer (surface finish, geometrical precision, manufacturing speed, etc...)

Step 2:

- No need to use STL interface
- Creation of native mode interaction with CATIA (1993) and other major systems (upon request).

III.1 The advantages of a powerful (>1 Watt) laser:

There are two main reasons for using a powerful laser; both reasons are constrained by resin technology (temperature control of an exothermic chain reaction):

1 Cost of the UV photon

2 Speed of the SPL manufacturing process

1. As we know, the polymerization reaction is economically efficient (it is a characteristic of most chain reactions) : a few Joules only are necessary to solidify 1 cm^3. The historical first generation SPL process uses today essentially UV lasers, which in turn produce some of the most expensive form of energy (Joules).Technical constraints (of laser manufacturing) impose that the cost of the UV energy (UV photon) is relatively less expensive, if and when one uses the most powerful lasers. There is more than a 10 factor between the 25 mW HeCd lasers and the larger useful (several W) Ar Ion lasers in terms of cost of the UV photon, including the investment cost of the laser, the cost of laser usage, and the replacement cost (statistical data given by laser manufacturers). All decisions leading to diminishing the UV photon cost will directly influence the new SPL machinery economic efficiency.

2. We should now underline that if we divide the effective part manufacturing time by 10 to 50, we will dramatically change current historical users outlook on the SPL technology, compared to other alternative RPT. A new user will not hesitate to make several trials before obtaining an acceptable new SPL product, if it takes only one hour to manufacture as opposed to 2 days ! We think that minimizing manufacturing time is not only important to minimize direct manufacturing cost, but also and most importantly, it is very important for allowing efficient trial/error sequences, which in turn will open faster new markets. In the fall 1992 we are putting on the market the SPL 1000/ LSA which should be around 10 times faster than actual competitors in recoating time (Appendix 1 line 5). Third party users will be able to make parts before the end of 92 on the SPL 1000 /LSA.

We are preparing, for 93 and/or as soon as our patents position is well established worldwide, a much faster version , the SPL 1000/LSB, which will again increase manufacturing speed as per the industry's numerous requests (International Conference on Rapid Prototyping, Dayton OH, pp.191,196).

III.2 Major problems associated with using high power lasers:

Except for the very low 0-10 mW range where inhibition problems occur in the photochemical reaction, the essential parameter governing the solid creation is the ratio laser **power/ scanning speed**. This means that if you increase the laser power you have to increase simultaneously the scanning speed to obtain the same results in terms of geometrical results (for a given spot size: brightness and depth of the polymerized line). In the case of a 1 Watt laser, the speed of the displacement of a typical 150 micrometer spot size required to bring up correct SPL parts is near 20 m/s (10-50 range), depending on the reactivity of the resin. Galvanometric technology is now capable of providing such scanning speeds, keeping proper accuracy in line (two years ago the problem of galvanometric mirrors inertia was drastically limiting the technology). We shall be using a 1 Watt laser this fall in Nancy. New patents have been filed (1992); they will allow the use of the most powerful commercial lasers available today on the market (7 Watts) for our 1993 SPL 1000 /LSB machinery. The increase of scanning speed is of course directly related to the speed of the SPL manufacturing process, but the efficiency of the

process should not be considered only in terms of scanning speed. In fact, the following figures will underline that in the liquid-solid technology, the most important source of inefficiency is linked to the recoating system (new patents pending):

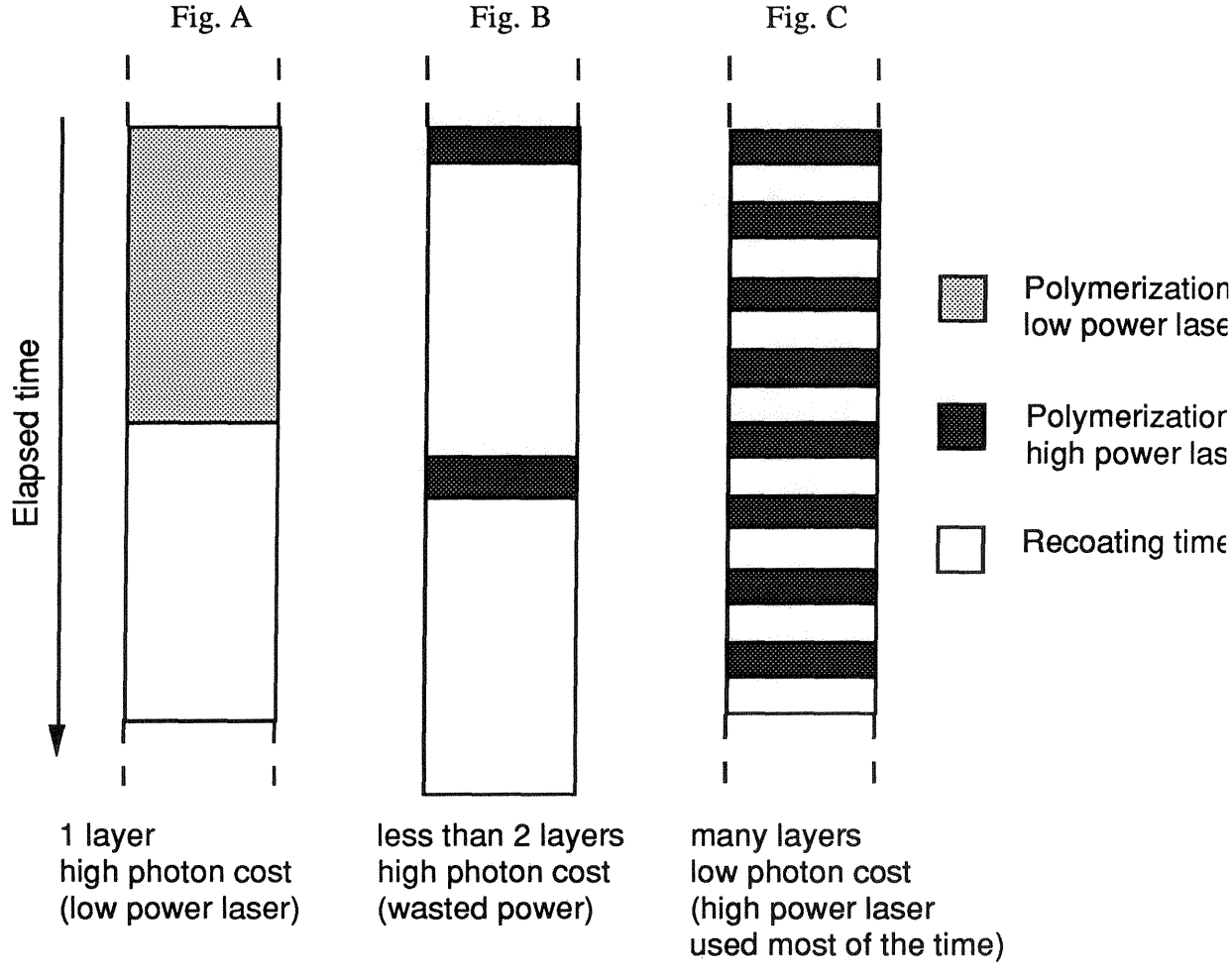


Fig. A shows that a small laser is properly dimensioned in the historical first generation SPL technology. One could therefore say that, given the current artificial constraints, first generation machinery is properly (not efficiently) defined.

In Fig. B, one can see that a high power laser (even infinitely powerful !) could only improve actual historical SPL global manufacturing speed by a factor of around 2; hence one could say in that sense (artificial historical constraints) that high power lasers are "inefficient" !

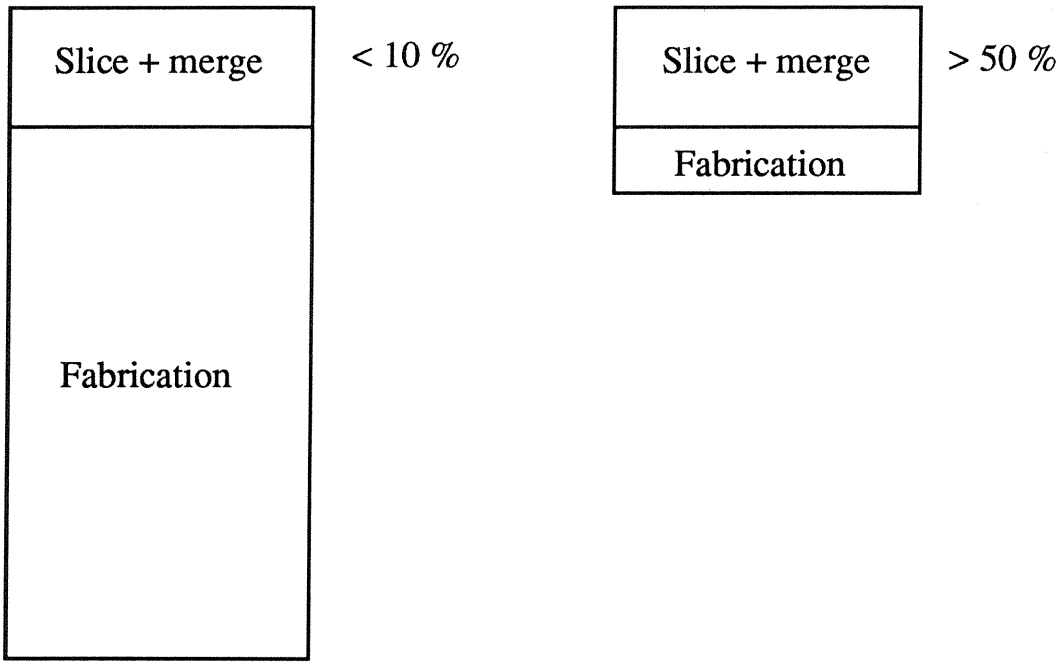
Fig. C is the proper objective for combining A and B: if one wants to obtain the "efficiency" of Fig. A, and the power usage of Fig. B, one must "balance" Tl and Tp durations (Tl: time required to lay an elementary layer, Tp: polymerization time).

That is why, while increasing laser power, one must dramatically diminish the minimum time required to properly lay an elementary layer, and this minimum time must be "almost" independent of layer thickness. The new second generation SPL 1000 LSA does include software adaptations and a new concept for installing properly elementary layers; our new second generation machine is designed as shown in Fig. C.One important additional point is

that the recoating time is "almost" independent of the viscosity of the resin; we can also therefore use low shrinkage viscous resins without being penalized by the recoating process. The use of low shrinkage viscous resins is interesting for limiting MACROSCOPIC deformations.

III.3 Other necessary improvements:

Most software preparation work imposed by the historical first generationSPL systems is in general (exceptions are possible) relatively small, hence not important, when compared to the part global manufacturing time.This "relatively small" preparation time for the historical SPL technology (in absolute terms compared to other RPT) is too high for the new concept SPL technology.



Therefore, if one wants to take advantage of a powerful laser, one must also define a new manufacturing strategy, where the new bottlenecks are properly managed. One must improve all manufacturing sequences by at least the same efficiency factors as the expensive increase in laser power. This imposed very substantial new SPL software design, and explains the reason why the second generation SPL 1000 /LSA is using much more powerful computers than the first generation SPL systems.

III.4 New solutions for the SPL 1000/LSA:

1 Access to efficient mirrors systems which allow the use of high UV laser power currently well above 1 W (up to 7 Watts)

2 A brand new concept (patents pending) for installing properly elementary layers

3 New SPL software (patents pending) allows, in particular, to prepare a new part during the manufacturing sequence of the preceeding one, to see the final aspect of the sliced part, to avoid adjustments of several parameters ("STYLES").

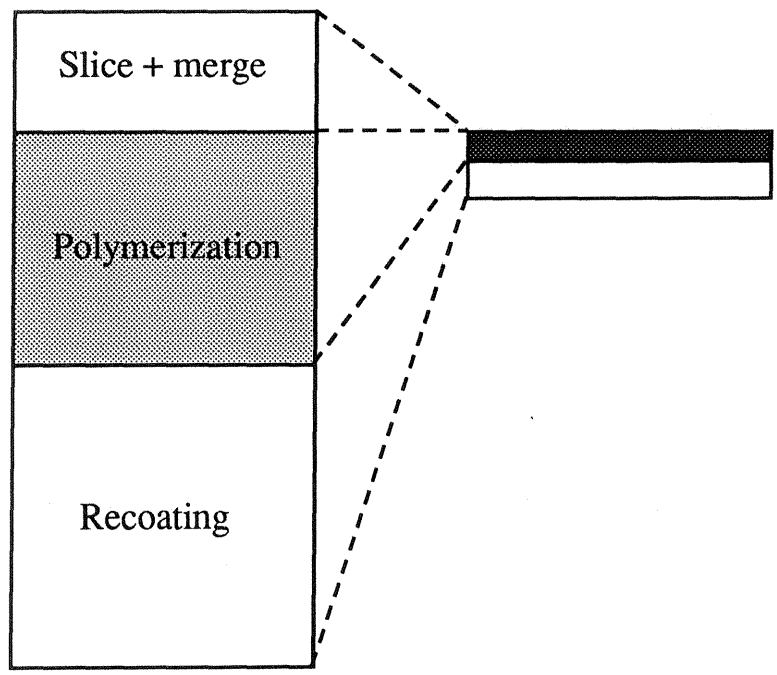
4 The mathematical slicing of the part takes place in parallel with (not before) the manufacturing sequence, which gives two additional advantages :

4.1 slicing time is strictly zero

4.2 No need to store "in advance" all computations necessary to define the SPL part.

Conclusions

The new SPL concept SPL 1000/LSA, integrating the whole knowledge of 5 years of experimentation, using high power lasers (> 1 W), leads to a new step in SPL technology, as can be underlined by comparing the historical (1988-91) and the new (1992) SPL technology :



APPENDIX 1: Technical specifications: comparative summary

	EOS 400	SLA 500	SPL 1000 LSA
Laser power (mW) +	25 to 300	200	>1 Watt
Maximal dimensions of the parts (cm3)	40x40x60 *	50x50x60 **	50x55x65 *
Typical scanning speed (m/s) +	1 to 10	2.5	10 to 50 (Typ. 20)
Spot location (micrometer)	±50	±65	±50
Recoating time (s) +	30 to 60	30 to 60	3 to 6
Minimal layer thickness + (micrometers)	100	127	<50
Slicing computer + (Mips/ Mflops/ SPEC)	26/ 4.6/ 20	option	58/ 12/ 50
Graphical performances + (vect. 3D/ s)	<220 000 °	option °	1 150 000 °°
Sliced parts memorization + (Mbytes available)		40	not necessary
Process control computer	486	386	486/ 33MHZ

* Removable

** Not removable

° No possibility to see the final aspect of the sliced part

°° Possibility to see the final aspect of the sliced part

\+ NEW CHARACTERISTICS: Second generation SPL- 100% improvement or above

FIGURES

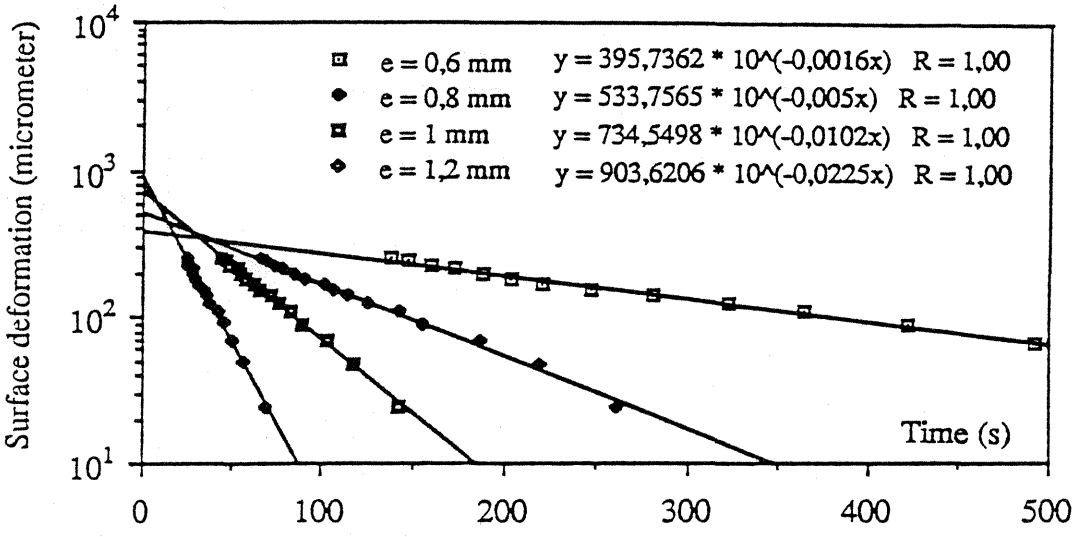


FIG. 1: Surface relaxation versus time for different layer thickness (e)

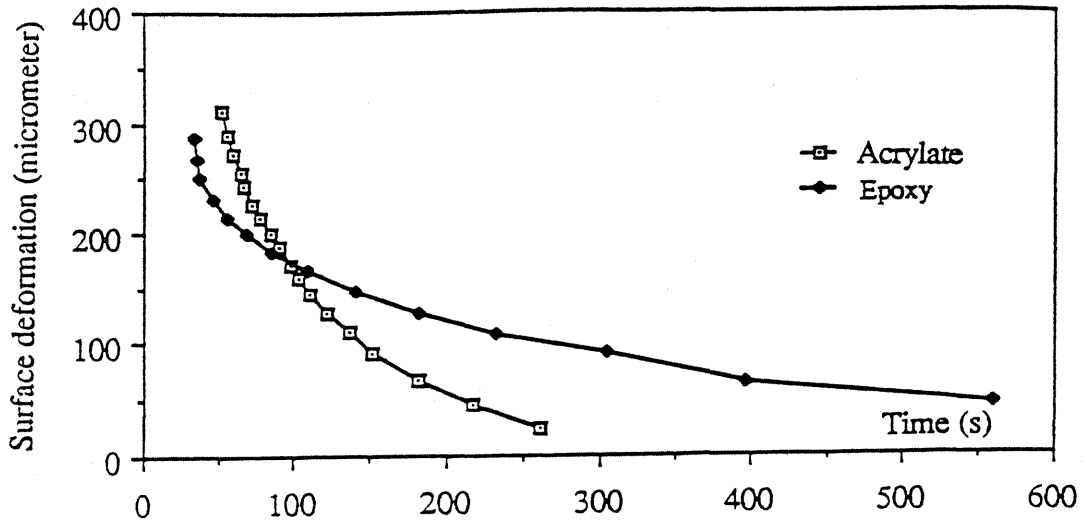


FIG. 2: Surface relaxation for two different resins

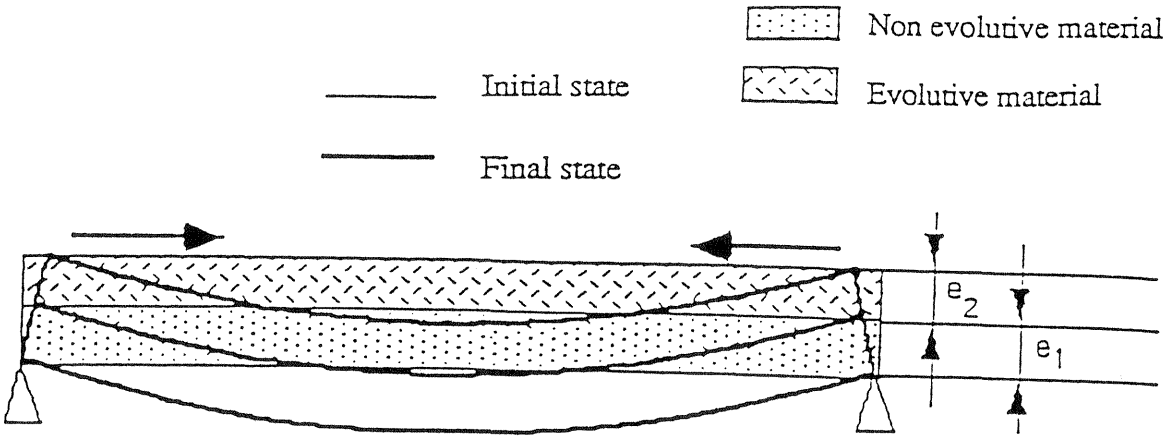


FIG. 3: Deformation induced by resin shrinkage (Simulation)

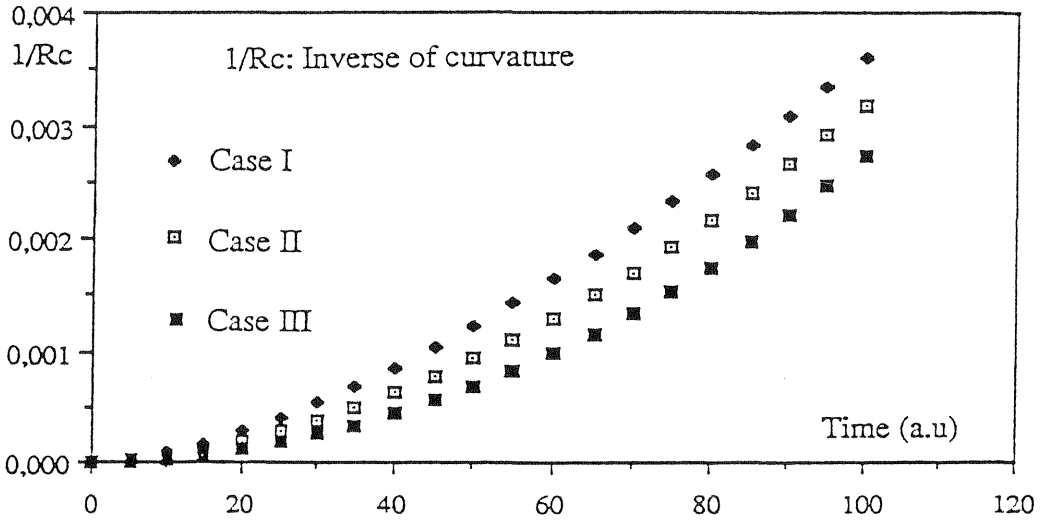


FIG. 4: Different time evolution of the deformation

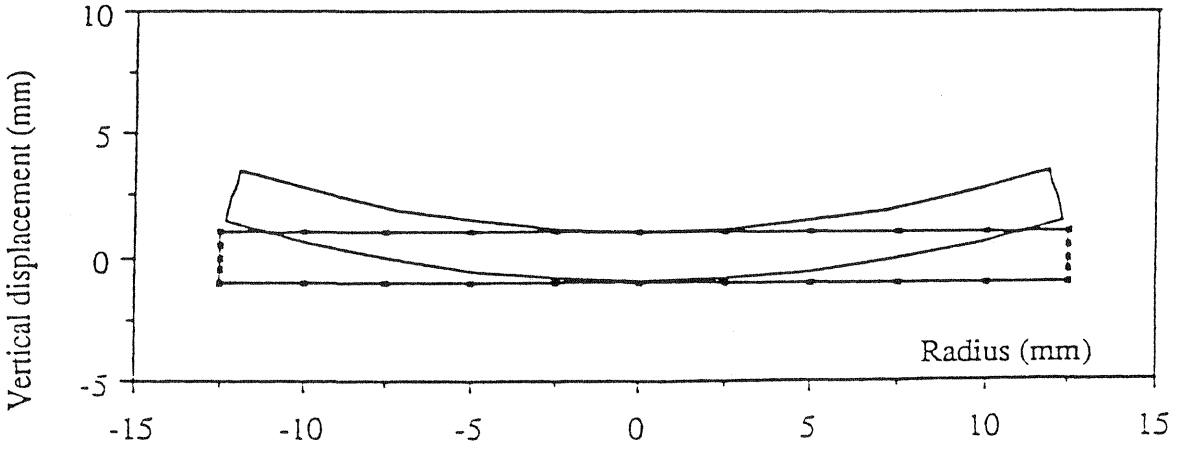


FIG. 5: Spontaneous deformation due to gradient effects (circular plate, simulation)