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DEVELOPMENT OF RAPID PROTOTYPING TECHNOLOGIES BASED ON LASER SINTERING

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ABSTRACT

This report describes the different activities developed during the BRITE/EURAM project entitled "Development of Rapid Prototyping Technologies Based on Laser Sistering". "This activities are clasified in three areas: Process Modelling, Process Engineering and Tooling Engineering.

The Process Modelling are is mainly centered in the development and validation of a set of codes based on the finite element method for the prediction of the characteristics of parts produced by Stereolithography (SLA) and Selective Laser Sintering (SLS) processes.

The Process Engineering area is centered in the development of new technologies for SLS processes. The development of laser sintering technologies to generate metallic prototypes is described mainly on examples of copper powder. In direct laser sintering processes low melting lead powder had to be incorporated with copper to supply particle bonds. Process parameters were optimized to minimize volume shrinkage and to improve particle and inter-layer bonds. Copper-1ead parts with limited layer numbers could be generated. Using a polymer material instead low melting metal as binder, fine and geometrically complex parts of copper, aluminum and stainless steel are built by means of laser sintering. A description of process chains to create fictional metallic prototypes is presented.

The Tooling Engineering area concentrates mainly on the study of possibilities that RP technologies offer for fast prototype mould production for the manufacture of small pre-production runs of pieces or the fine tuning of' technological processes.

INTRODUCTION

Parts produced by RP techniques present some distortions that sometimes can exceed from specific tolerances. In the SLA processes, one of the main sources of error in the final dimensions of the prototype is the cud distortion effect owing to the shrinkage of the resin when it solidifies during its solidification during the building process. The numerical prediction of this distortions has to take into account the layer by layer nature of the building process, the shrinkage of the resin during the building process and during the postcuring, and the additional deformations that can be produced when the part is separated from the building platform.

Part distortions are also present in SLS process, but in this case they are mainly due to the big changes of density of the sintered material with respect the powder material. The numerical analysis of this type of processes has to follow the sintering process produced by the incidence of a laser beam that elevates the temperature. For the prediction of how the material is sintering it is necessary to know the history of the temperature distributions in the material. This temperature distribution depends on the power on the laser beam and on the thermal conductivity of the material. This conductivity depends on the density and the density depends on the degree of sinterization of the material which converts all the problem into a coupled one.

in contrast to the most rapid prototyping techniques different materials (polymer, metal and ceramic) can be processed by laser sintering. Laser sintering of polymers, for example PS, PC and PA, has found a lot of industrial applications. Because of restricted thermal and mechanical properties of polymers, metallic or ceramic prototypes are required increasingly in the industry [1,2]. Producing metallic and ceramic parts using laser sintering technologies might open a great number of new application fields. In the following investigations of laser sintering of metals will be reported.

RP allows an exact physical representation of a product from a computer database without regard to complexity, without generating engineering design drawings, and without machining or tooling processes. Even so , it has its drawbacks: generating large batches of production material prototypes, for example, is impossible. Industry is now searching to overcoming these limitations. The present solution involves the application of rapid prototyping as a pattern generator for secondary processes.

The preparation of prototypes and the manufacture of tools for forming and casting processes, referred to as Rapid Tooling (RT), is a sector of considerable interest, since it provides designers with a quick way of obtaining parts for the very much earlier completion of both technical and economic analyses. RT is particularly suitable for the creation of casting moulds and dies, since it can readily cope with complex geometries in addition to providing the time and cost savings already mentioned. The iterest of the Tooling Engineering area is mainly concentrated on the study of the possibilities RT offers for mould for resin injection fabrication for the manufacture of small pre-production runs or fine tuning of the technological injection process.

TECHNICAL DESCRIPTION AND RESULTS

Advances in the Process Modelling area

Mesh generation

The main part of the mesh generation task has consisted in the development of an algorithm to get a piecewise linear approximation of trimmed surfaces. This approximation is used as a triangular discretization of the surfaces of the different prototype parts to be analyzed starting from the CAD definition of the geometries. It is also used as a good tool to get STL files.

The main goal of this work is to obtain a triangulation of the boundary surface of an object represented by a standard surface model (IGES or VDA). The original object is represented in terms of trimmed parametric surfaces, which form the boundary of the solid. The resulting approximation cannot exceed a tolerance value, provided by the user. In addition, there exist several extra conditions for the resulting triangulation which come from the analysis requirements:

- The triangulation has to be conformal. This implies that there cannot be cracks between neighboring triangles.
- The shape of the triangles has to be optimal in the sense that they have o be as close as possible to equilateral triangles. This condition can be expressed in terms of the angles of the triangles, the called max-min angle criterion.
- The number of triangulation vertices has to be minimum.

The main application area of this work is stereolithography of CAD designs, but it can also be extended to other areas as finite element analysis or rendering of surface models.

In order to construct the triangulation of the patches bounds for the linear approximation are used. These bounds are directly related with the curvature of the geometric elements. The bound for curves limites the maximum length of an edge allowed for a linear segment that approximates a curve, and the bound for surfaces indicates the maximum allowed length of an edge of any triangle that approximates the patch. Because an adaptive approximation is desired, a quadtree of bounds is built foe each patch instead of using a simple bound for the whole surface.

The implementation of the algorithm first reads data from a CAD file containing the description of the object to be approximated. The VDA format has to be chosen for these files because it is one of the standards that allows trimmed surfaces. Next, it checks whether the data describes a correct closed solid by analyzing supplied topological information and building new entities if necessary

After the previous steps a preprocess of the triangulation is performed. It consists in the calculation of the bounds and the construction of the quadtrees for ecah face of the solid. Given these tools, the trimming curves are discretized providing the edges of the solid. The next step is to construct the adaptive triangulation of each face. This is done in three sub-steps: first, the number of points to be placed inside each face is computed; second, the vertices are placed in order to obtain a good triangulation; and finally, the triangulation is constructed. The number of points is computed using the quadtree of bounds previously generated. The vertices are placed first sitting them randomly distributed on the parametric plane of each face and then repositioning them using a relaxation process that uses repulsion forces between the vertices.

As one of the goals is to obtain good-shaped triangles a Delaunay triangulation is used which guarantees the min-max angle criterion. The obtained triangulation is stored into a file which can be used for different purposes: starting point to built a three dimensional finite element mesh; create an STL file to supply geometric information to any rapid prototyping building process; and supply information for rendering processes.

A finite element mesh generator has been developed to get the analysis grid starting from the surface triangulation. This mesh generator provides a mesh which follows the layer by layer structure of the rapid prototyping building process. The elements are distributed by consecutive layers whose boundaries are located on the triangulation of the surfaces. The developed algorithm can start from any conformal triangulation of the surface. This triangulation is normally provided by the previously described method, but it can also be provided by an .STL file coming from anywhere.

The generation of the finite element mesh starts with a cutting process of the surface triangulation. This provides a poligonal description of the geometry of each layer of the rapid prototyping process. A planar structured finite element mesh is generated on each layer and then all the layers are connected to provide the three dimensional mesh for the analysis.

Finite element model for SLA processes

A finite element model has been developed to simulate part distortions during the SLA building process. The SLA process has beer-i carefully studied in order to obtain the main assumptions for the development of the numerical model. Part distortions are mainly due to the additive layer by layer construction process together with the shrinkage of each layer after its solidification. This two characteristics of the process produce the so called “curl distortion" which is schematized in Figure 1 for a trivial case. The layer by layer sequence and the shrinkage of the resins are assumed to be the two crucial aspects of the part building SLA process. The amount of shrinkage depends of the type of resin and the laser tracing algorithm employed for the part building process. The numerical model developed for the analysis has been developed in order to include all these aspects.

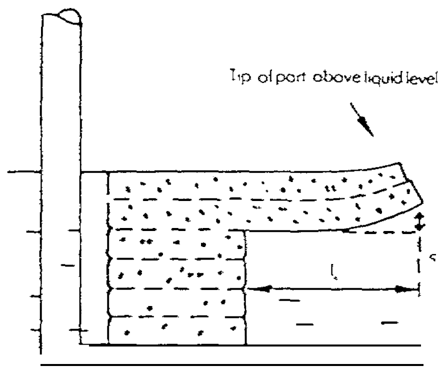


Fig. 1 Curl distortion

The complete SLA process can be summarized in the following steps:

- Part building process where the prototype is built attached to a platform using a layer by layer process. Each layer shrinks after its solidification.
- Post curing process where the whole part is cured in order to produce the solidification of the remainign liquid resin. This produces an additional volumetric shrinking of the whole part with additional distortions. This process is performed with the part still attached to the platform.
- Separation of the part from the platform. At this stage the residual stresses produced during the post curing can produce additional distortions.

The numerical model developed in this task follows the same steps than the SLA process. A first 2D version of the code has been used to test the basic features of the model. Also, a 3D version has been developed and tested. These codes are based on the following assumptions:

- The finite element mesh follows the layer by layer structure of the process. There is a layer of elements corrsponding to each layer of the SLA process.
- The analysis of the part building process is performed in a step by step manner. At each step a new layer of elements is added to the previous part. After this addition, the new layer shrinks producing a distortion of the whole part.
- A special algorithm has been developed for the addition of new layers over previous parts in order to avoid negative area elements. It is based on an appropriate location of the new nodes corresponding to new layers.
- The post curing process is modeled assuming that a uniform additional shrinking is produced on the whole part after the part bulding.

- When the part is removed from the platform the previously existing forces attaching the part with the platform are applied in the opposite direction to the part.

- At the actual stage the model assumes a linear elastic material model for the resins employed for the SLA part building processes.

In order to calibrate the finite element model it is necessary to get the shrinking factor corresponding to each stage for each different resin and laser tracing algorithm. A simple experiment has been used to get this factor for each different case. This experiment consists in the analysis of a twin cantilever part (see figure 2) and a comparison with existing experimental results. Several finite element analysis of this simple part have been performed using different shrinkage factors for the part building and the posturing processes. The experimental values are compared with all the analysis and the shrinking factors corresponding to the closest analysis values is chosen. This factor is then used for the analysis of more complex parts built with the same resin and laser tracing algorithm. A shrinking factor equal to 0.0017 has been obtained for the building process.

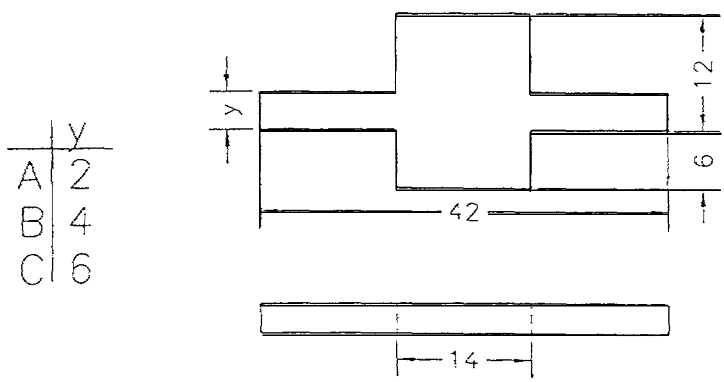


Fig. 2 Twin cantilever part.

Figure 3 shows a superposition of the defined (only one half) and distorted geometries obtained for one of the computed cases.

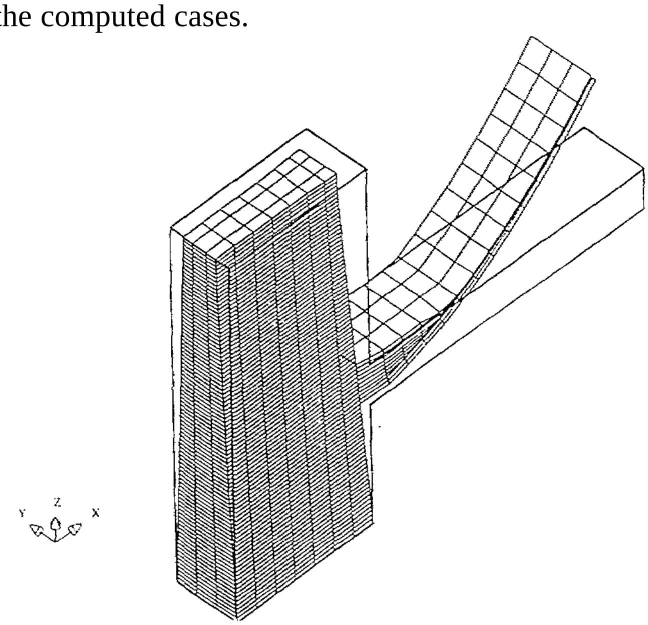


Fig. 3 Superposition of the defined and distorted geometries.

The twin cantilever part has also been used to check the influence of different factors in the analysis like the Young and Poisson moduli and the layer thickness. The conclusion of this work is that the use of the correct values for the Young and Poisson moduli are less important than the correct layer thickness and shrinking factor. This will be very important for the analysis of different parts because the most important care will be devoted to the correct evaluation of these iast parameters.

The so called User Part has also been used to check the developed computer codes (see figure 4). This part is of common use for the calibration and comparison of different rapid prototyping technologies and many experimental results can be obtained for it.

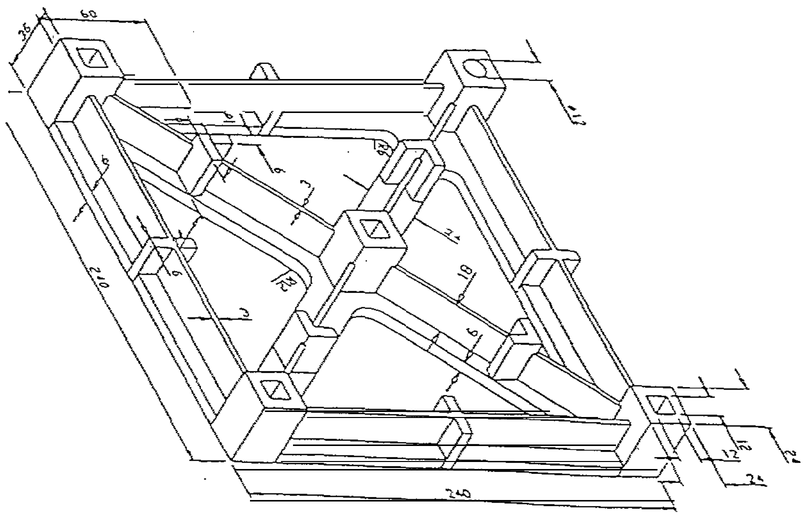


Fig. 4 User Part.

Figure 5 shows a superposition of the defined and the distorted User Part obtained from the analysis. A very good agreement has been obtained between this distorted geometry and the experimental measurements. Additional details about this model can be obtained in referece 4.

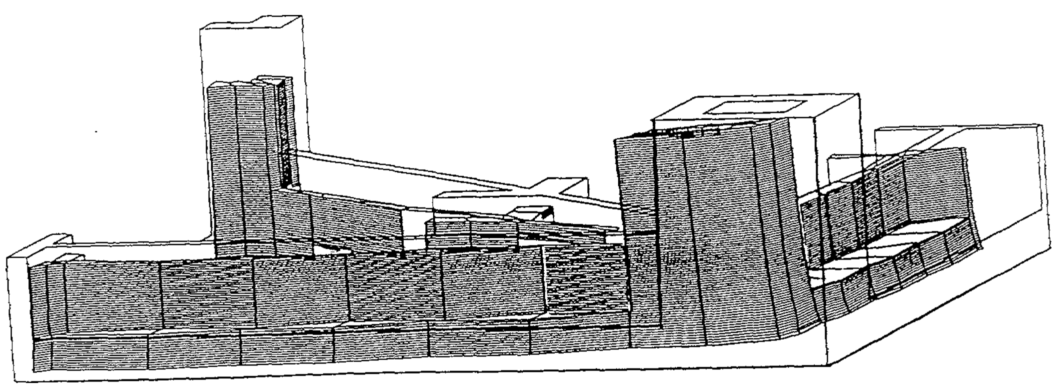


Fig. 5 Superposition of the defined and the distorted User Part.

Finite element model for SLS processes

A finite element program has been. developed to simulate a three dimensional model for selective laser sintering based on the basic model structure: optical-thermal and sintering submodels. Combining these submodels, a three dimensional simulation is developed. This model can be used to evaluate important process properties that affect the quality of sintering such as sintering depth and thermal stresses. In addition, a mechanical model has been used to simulate the stresses and strains that appear during the sintering process. This mechanical model uses the information coming from the sintering model.

Selective Laser Sintering processes consist of three stages (see reference 5):

- A layer of powder is deposited on the elevator and pressed; each layer of powder is preheated before the scanning to minimize the need of induced laser.
- Laser radiation sinters the powder to form the profile of the section.
- The elevator drops through a distance equivalent to the thickness of the section, and the process is repeated until the prototype is completed.

The materials employed are nylon, polycarbonate, ABS, and metal powders. The physical process associated with this process includes: laser absorption, heat transfer, and sintering of powde. The sintering models in the study are based on the analysis of Scherer and Mackenzie-Shuttleworth (see references 6,7,8,9). In this analysis, knowing the temperature at a position in the powder bed, the sintering rate can be calculated and the density change as a function of the sintering rate.

In the other hand the conductivity of the particle bed is a function of the density in the heat conduction analysis. For this fact, it has been observed that a non-linear general purpose finite element program can be adequately used for modeling the coupled thermo-sintering problem.

The program modelled the resulting temperature and density distribution in the powder bed, when the heat source is fixed at an specific position and time.

Thermal model

The heat transfer behavior in the powder bed can be described by the standard conduction equation. In contrast to the conduction problem of a solid material, the thermal conductivity of a powder bed can vary from position to position depending on the local temperature as well as the condition of contact between particles and the local porosity. Yagi and Kunni (ref. 10) have formulated a model for effective conductivity of a packed bed considering the conduction, convection and radiation effect within a powder bed.

An empirical model has also been developed by Xue (ref. 11) especially for Selective Laser Sintering powder.

Using these models, the temperature field in the powder bed can then be solved by integrating the thermal model using a numerical method.

Sintering model

To follow the evolution of the density (or void fraction) as a function of time and temperature, in this work the Scherer and the Mackenzie-Shuttleworth models have been used (ref. 6-9). Both of these models assume that the surface energy reduction of the sintering powder drives the process through viscous mass flow dissipation. In the lower density range the powder is assumed to consist of an open pore network of cylinders arranged cubically, with the cylinder diameters equal to the particle diameter and the cylinder lengths proportional to the pore diameter. As sintering proceeds, the cylinder heights collapse, reducing the void fraction in the powder bed, until the cylinder walls touch one another. At this point the situation can be described contiguous spheres with closed pores.

As the particles sinter, the void fraction drops. The Scherer model gives an expression for the void fraction as a function of the cylinder aspect ratio in the unit cell.

Mechanical model

The mechanical model solves an elasticity problem using the information coming from the sintering process. This information consists in the changes of the density distribution during the time.

It has been considered that far away from the laser beam the mechanical problem can be simplified into a two-dimensional one formed by a transverse cut of the sintering domain. In this simplified domain each node is subjected to a evolution of its density that produces a certain history of deformations.

For each increment of time there is a change of density that produces some initial deformations. For each increment of time the Young modulus and the Poisson ratio are obtained in terms of the relation of the actual density and the fully sintered material density. After the obtention of the deformations and distortions corresponding to a given increment of time the geometry is actualized and the next increment is taken.

Solution strategy

Using the finite element method, the conduction equation together with the sintering model are solved. That equation leads a non-symmetric system of discretized equations, The nodal temperature distribution resulting is used in the sintering subroutine to calculate the density distribution. In this subroutine, the sintering model described above was implemented.

A three-dimensional computer simulation program has been developed. This program is based on the finite element method and it includes the ingredients previously mentioned.

Figure 6 shows. the final distorted geometry and the interrnal residual stresses corresponding to four different time steps corresponding to the laser sintering of a single track of a policarbonate material,

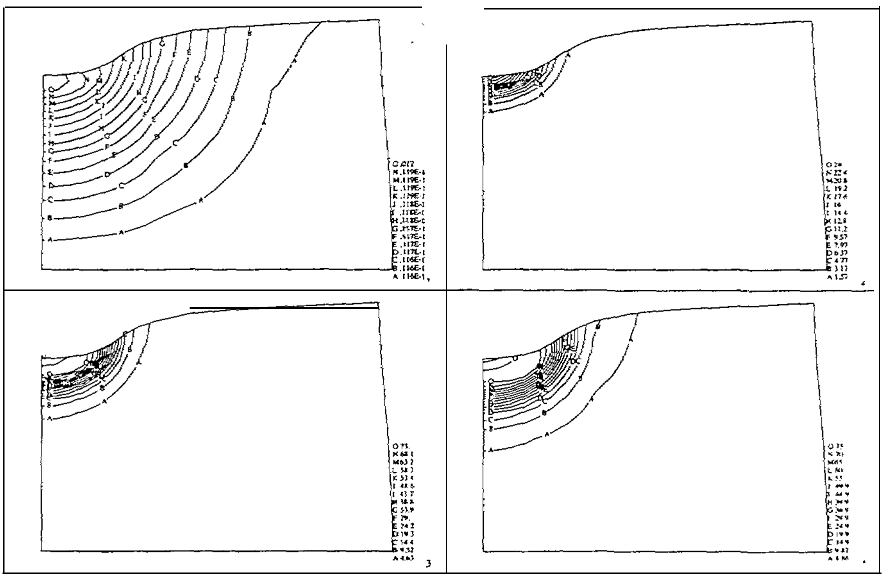
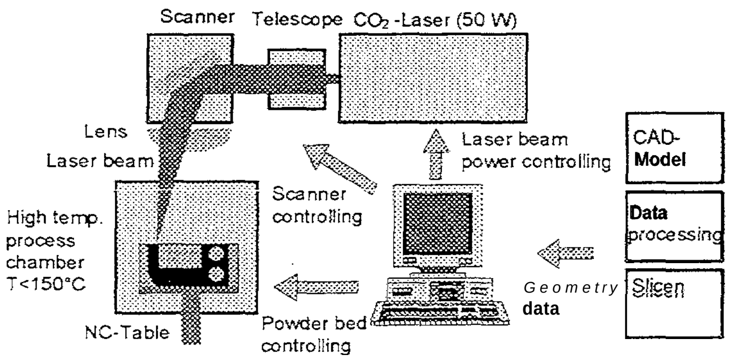


Figure 6 Deformed geometry and residual stresses for a sintered sigle track

Advances in the Process Engineering area

The main pm-t of the investigations was earned out using a special laboratory equipment for laser sintering, installed by EOS GmbH (Munich/Germany). Its specifications and components are described in Figure 7.

Starting materials are powdered copper particles having the particle size of 45 to 90 pm, which will be bound due to elevated temperature by laser irradiation to form a 3D part. Because of the extremely short interaction time between the laser beam and copper powder high temperatures in the powder bed cannot be kept long enough to accomplish diffusion controlled sintering processes. Therefore, particle bonds and consequently the strengths of sintered copper parts are generally low.



1. Specifications of the machine:

Laser beam power	50 w
Beam diameter	0.4 mm
B-earn scanning velocity:	10 to 10000 mm/s
Temperature OF process chamber	≤ 150 °C
Step of CNC table	0.15, 0.2 mm

Figure 7 A sketch and specific data of the laser sintering laboratory equipment.

Laser sintering processes can be accelerated by creating a liquid phase partially in the powder bed, which is available when a low melting metal (for example lead) is incorporated into copper powders. As the liquid lead wets the solid copper particles, its surface tension provides driving forces for sintering processes. A prerequisite for liquid phase sintering is to chose a appropriated processing temperature between the melting points of both materials. In comparison copper-lead powder has not only a much wide process working area (Figure 8) but also substantially higher green strength than pure copper. The SEM-micrographs [Figure 9) show the increasing powder bonds with rising lead content,

Curl formation is an essential problem in laser sintering. It is caused by internal stresses due to volume shrinkage of powder materials. In case of brittle particle bonds cracks occur. If particle bond is strong enough to stand the stresses but not soft enough to reduce them without macroscopic deformation, curl appears. Therefore, the strategy to eliminate curl appearance is either lowering volume shrinkage, for example the nickel-bronze-based alloy used by EOS [3], or secondly to enable yielding of particle bonds. This is possible if metal powders are incorporated with polymer binders.

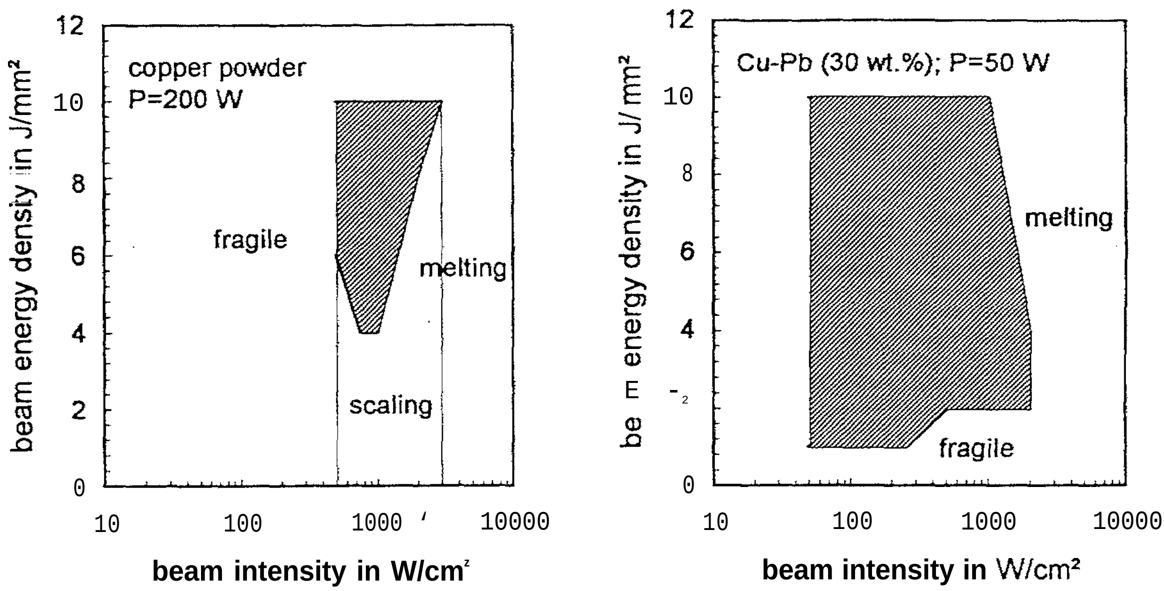


Figure8 **Process working areas for** laser sintering **of copper and copper-lead powders** at **beam power of** 200 **and 50 W, respectively. Pure copper powder couldn't be laser** sintered at **P=50 W**

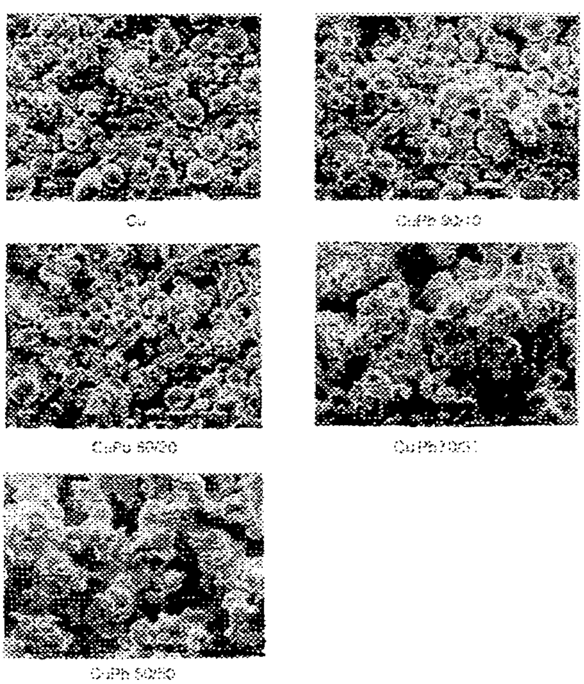


Figure 9 SEM-micrographs **of cross sections of** sintered **copper tracks containing different lead** additions, P=100 **W,** I=500 W/cm², **H=4 J/mm².**

The investigations on pure copper-lead show that the volume shrinkage in CuPb powders depends strongly on process parameters and cannot be eliminated completely. The trick to build a 3D part is at one side minimizing the volume shrinkage and on the other hand to bind the layers tightly. In experiments the first layer was bound to the substrate by means of an low melting alloy coating on the substrates. Pure metal part of about 5 mm thickness were generated. Thicker parts showed statistically appeared delamination faults, which can be avoided if recoating accuracy is improved. The average surface roughness in horizontal directions is about 50 µm.

Laser sintering of metals containing polymer binders

If powder mixtures of metal and polymer binder are heated by laser irradiation the polymer material starts to flow and fills powder cavities partially. It supplies sufficient particle bonds and annihilate internal stresses without curl formation. After numerous tests a special nylon based polymer was found appropriated particularly to serve as binder material. Copper, copper-lead, aluminum and stainless steel powders can be laser sintered in wide process working areas which are similar for all materials. The process is reproducible and stable against deviation from optimum parameters. Figure 9 shows examples of laser sintered parts of these metals.

The geometrical accuracy in x- and y-directions can be affected by adjusting the gain factors of the corresponding scanning mirrors. For a maximum length of 95 mm it can be minimized to 0.1 mm. The deviation in z-direction is less than 0.3 mm. The laser sintered parts have generally a low density because of the low packing density of not compressed powder materials. It might be increased slightly because the binder material is capable of filling powder cavities. On the other hand overheating can decompose and vaporise the polymer material. The final density of laser sintered parts is therefore influenced by polymer content and process conditions. The higher the polymer content, the more dense the laser sintered parts. In case of laser sintered copper parts the relative density was in the range of 50 to 70%.

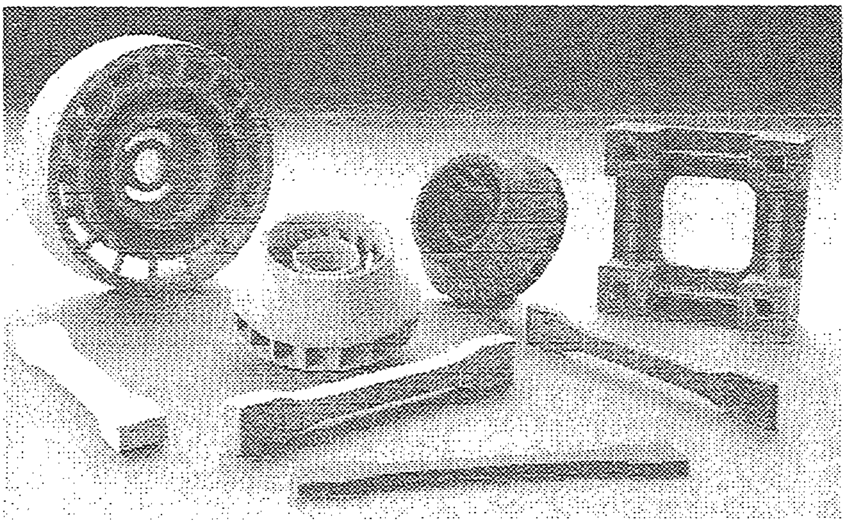


Figure 10 Exampies of laser sintered parts of copper, copper-head and aluminium powders containing polymer binders.

The roughness values of laser sintered parts differ to each other depending on measuring directions (Figure I I). They are in the horizontal directions about 50 µm. In the vertical direction it depends on the polymer content. For samples containing less than 30 vol. % polymer binder the vertical roughness is twice of the horizontal roughness. For parts containing more than 40 Vol. 0/0 binder the roughness values are almost the same as those in horizontal direction. The roughness of laser sintered parts are also influenced by other process parameters: traverse velocity and hatching distance. Generally “small hatching distances result in a low roughness. It inclines as beam energy density (depending on the velocity and hatching distance) rises. At the moment when polymer is being decomposed by overheating, roughness values increase with the beam energy density.

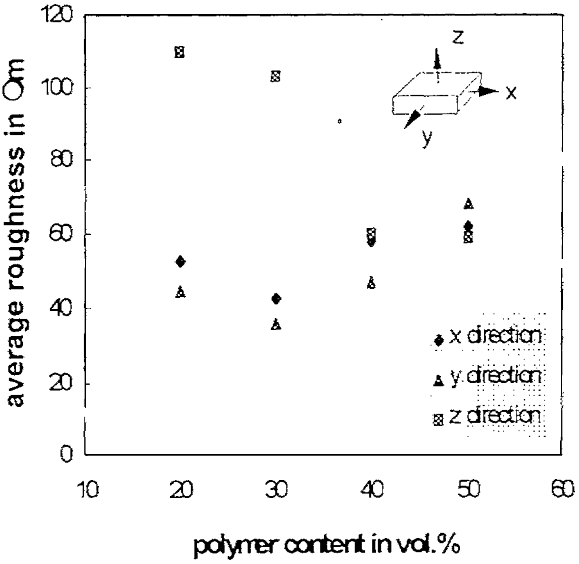


Figure 11 **Roughness measured** in x-, y- and z-direction of laser sintered parts.

Laser sintered parts have comparatively low green strengths and cannot be used as functional prototypes. They have to be postprocessed to get higher density and to improve their properties. Process chains to produce a metallic prototype using laser sintering technology are presented in Figure 12. Here laser sintering serves only as a forming process to generate 3D parts with green strength, rather rough surfaces and high porosity. The debindering after surface finishing brings them to high porous „brown" parts with even less strength than the green parts, The infiltration or final oven sintering will give them the nearly full density and metallic properties. The first debindering experiments show that the geometrical form can be retained if debindering temperature was controlled exactly.

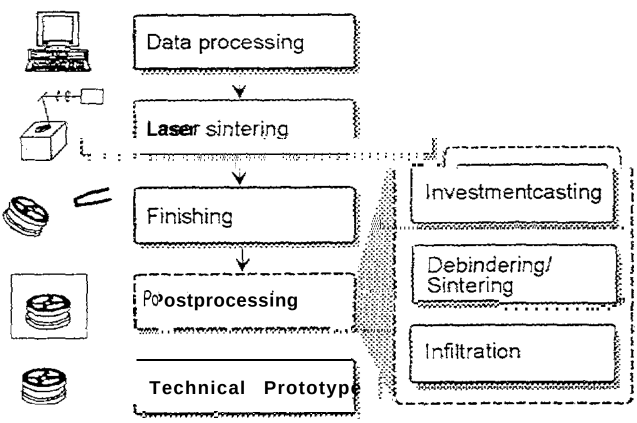


Figure 12 **Process chain to generate metallic or ceramic prototypes using laser sintering technology.**

Conclusions

Process working areas are established to get laser sintered parts with sufficient green strength and no cracks. Copper-lead (40 vol.%) parts can be generated at limited number of layers. Thicker parts have statistically appeared delamination faults which are supposed to be caused by inaccuracy of powder recoating.

Curl formation is the most critical problem in laser sintering. It can be avoided by eliminating volume shrinkage or using polymer binders. The addition of polymer binder to metal and ceramic powders enhances their feasibility for laser sintering processes, The polymer is responsible for process stability and reproducibility. Divers metals (copper, aluminum and stainless steel) can be laser sintered.

The accuracy of laser sintered parts is in x- and y-direction about *O. 1 mm and in z-direction less than ±0.3 mm. The relative density of green parts ranges from 50 to 70 % while the roughness is about 50 pm. The copper parts could be debindered without losing their geometrical shapes,

Advances in the Tooling Engineering area

During the first part of our the work in this area it reached the conviction that the progress of selective laser sintering (SLS) is being hindered by the objective difficulties raised in attempting to enlarge the working chamber, and to sinter materials other than thermoplastic resins. Therefore, these difficulties mean that SLS will be regarded as a marginal technique confined to applications where the dimensions are small and the part required can be made by investment casting. Attention was concentrated also to other RP techniques. Once all the available technologies had been identified, the first problem tackled was the checking of some basic features of the product, i.e.:

- *dimensional precision*
- *dimensional stability over time*
- *surface features such as: roughness and porosity*
- *rheological features of the different materials*

the technical literature on these properties is very scanty or even non-existent:

To obtain at least some of the information required, it was decided to use the object known as a “user-part”, Originally proposed in the USA by the Stereolithography Users Group and subsequently adopted *as* a reference standard by 3D Systems Inc., this is still regarded by competitor technologies as a yardstick for comparison with stereolithography itself. A few slight variations were made to this object to adjust its measurements to the metric system. Seven different technologies were employed to produce the user part in nine different materials.

Evaluation of the deviation between the real and the nominal dimensions, calculation of the relative value of the standard tolerance factor, and conversion of the absolute deviation values into tolerance values. The aforementioned variable is defined, according the ISO-ANSI requirements, in the following manner:

$$i = 0.45 \cdot \sqrt[3]{D} + 0.001 \cdot D$$

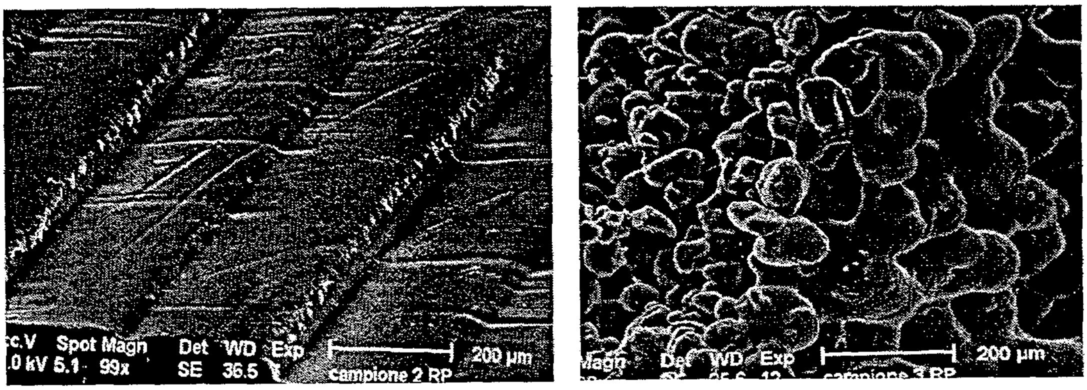
where D is the nominal dimension

The results obtained show that al the RP parts lie within the ranges of grades IT13 & IT 14; figure 13 puts in comparison tolerance grades for various manufacturing processes and RP.

Surface finish and surface morphology are very important aspects to be considered for the purposes of the job The parts are examined at the SEM; figure 14 puts in comparison the layer produced with SLA and that one produced with SLS.

	IT GRADES										
Process	6	7	8	9	10	11	12	13	14	15	16
Sand Casting									■	■	
Die Casting						■					
Hot Forging							■	■	■		
Material Removal Processes	■	■	■	■	■	■					
RP techniques									■	■	■

Figure 13: Comparison of Tolerance grades for various manufacturing processes including RP



a) b)

Figure 14: Micrographs **showing the** layer **of parts produced with :**
a) **SLA** by **3D Corporation**
b) SLS by DTM

Examination of the results of this study and close examination of the problems associated with the fabrication of a mould showed that the user-part as such allows good assessment of the intrinsic precision of a machine, the repeatability of a process, and the porosity of the surface produced, whereas it is unsuitable for evaluation of the performance of RP in the creation of the non-flat surfaces typical of moulds, whose multiplicity of shapes is well illustrated by the plastic parts used in car construction, or the small objects used in offices or for finishing.

The original user part, in fact, is not a true 3D solid, but what is called a body with 2 1/2 axes in mechanics. It is thus unaffected by facetting and slicing (except at its fillets).

A true 3D solid object was proposed able to show the effect of all operations. In addition, since it is a shell, it provides a very clear illustration of any shrinking that may take place. A solid object comprising some of the typical shapes presented by manufactured parts, Fig. 15, has thus been devised.

STP does provide much information essential for the purposes of work by allowing:

A. Evaluation of precision in the reproduction of non-flat surfaces through the determination of both dimension and shape errors.

B. Measurement of the roughness of both non-flat surfaces and fiat surfaces not parallel to the co-ordinate planes.

C. Reproduction of very small parts, such as unions of various sizes.

D. Creation of relatively thin walls with non-flat edges.

E. Evaluation of the performance of the post processors typical of each technology;

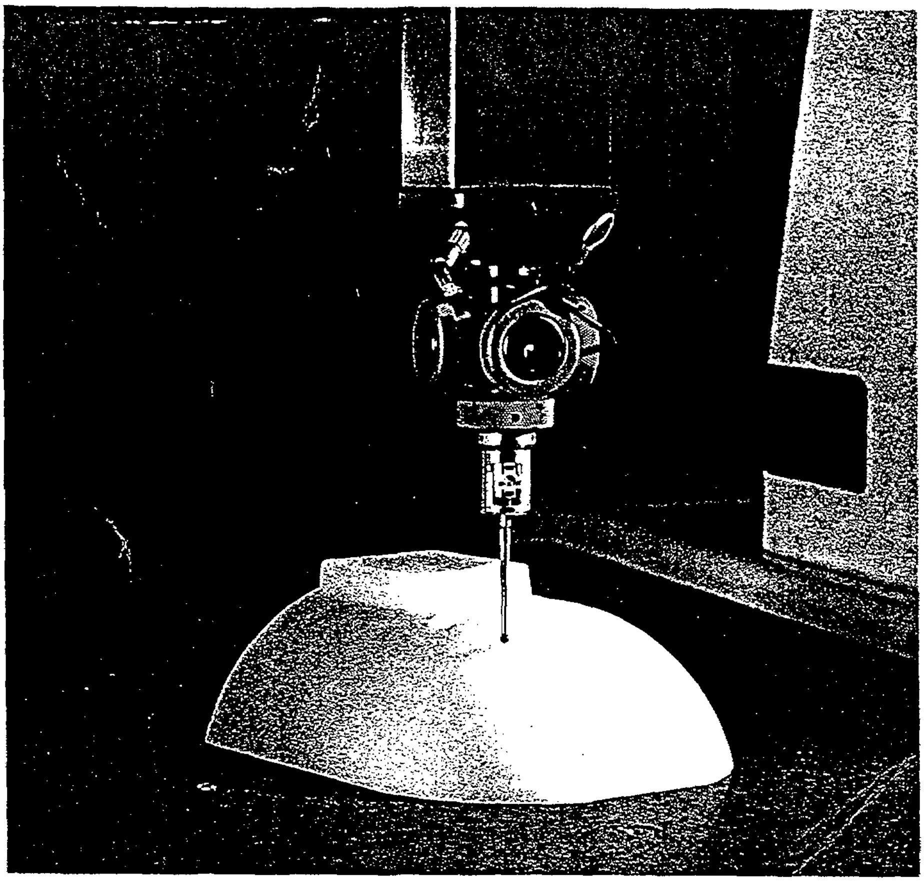


Figure 15: Shell test part (STP)

At the end of the first half of the research activity it is possible to affirm that: SLA and SLS (respectively Stereolitography and Selective laser sintering) offer the best precision.

SLS shows a better stability over the time but SLA gives a better surface finish, bigger working area (till 1000 ‘ 500 ‘ 500 mm) and moreover it is less expensive and more diffuse.

The SLA was used to produce a female model and a male model sized down to allow for the thickness of the part to be produced. These two models are then used to make resin copies need to create the two platens by metallisation. This additional step. however, is included for two reasons: to allow finishing of the two models by removing the traces of the slicing operation (we can always operate on a male part) and to prevent destruction of the initial model.

Two technique are employed to produce the metallic replicas: metal plating and thermal spraying. The thickness of the shell was in both cases of about 5 mm,

Metal plating offers a more smooth and hard surface then thermal spraying but the last one is less expensive and quicker to be produced (a few hours against a few days).

A mould was designed with two-equal figure mould with metal inserts obtained applying the two cited techniques. In this way it will be possible to compare the life and the behaviour of the two metallised layers subjected to identical stresses and temperature. Each pattern was made by the steel cylindrical body and the figure mould. The figure mould is connected to the steel body using an epoxy resin. The epoxy resin was charged with metallic particles in order to improve thermal conductivity.

This filler was a very delicate matter; in fact:

- it must ensure sufficient mechanical strength in order to support the forces during the injection (**10...100** MPa);
- it must tolerate temperature of about 100..1**50** °C without lost its mechanical properties
- it must **have** low viscosity before polymerisation in order to fill the wide between the pattern and the body;
- it must have high thermal conductivity

Fig.16 shows the picture of die and punch of the mould; the copper tube are used to water cooling the pattern Thermocouple are inserted in the filler to control the temperature during the injection phase.

The test has shown that the two pattern are able to produce more then a few hundred parts, Figure 17; the pattern electroplated produces a smooth surfaces of the plastic part then the pattern obtained by thermal spraying. The injection pressure may range between 10...5⁰ MPa without producing plastic deformation of the filler or mechanical breakage of the metallic shell. Attention my be paid to the. injection cadence to avoid an increase in the temperature of the filler.

As a conclusion of this sub-task may be said that the proposed technology is suitable to be improved in order to be industrially employed to produce fictional prototypes.

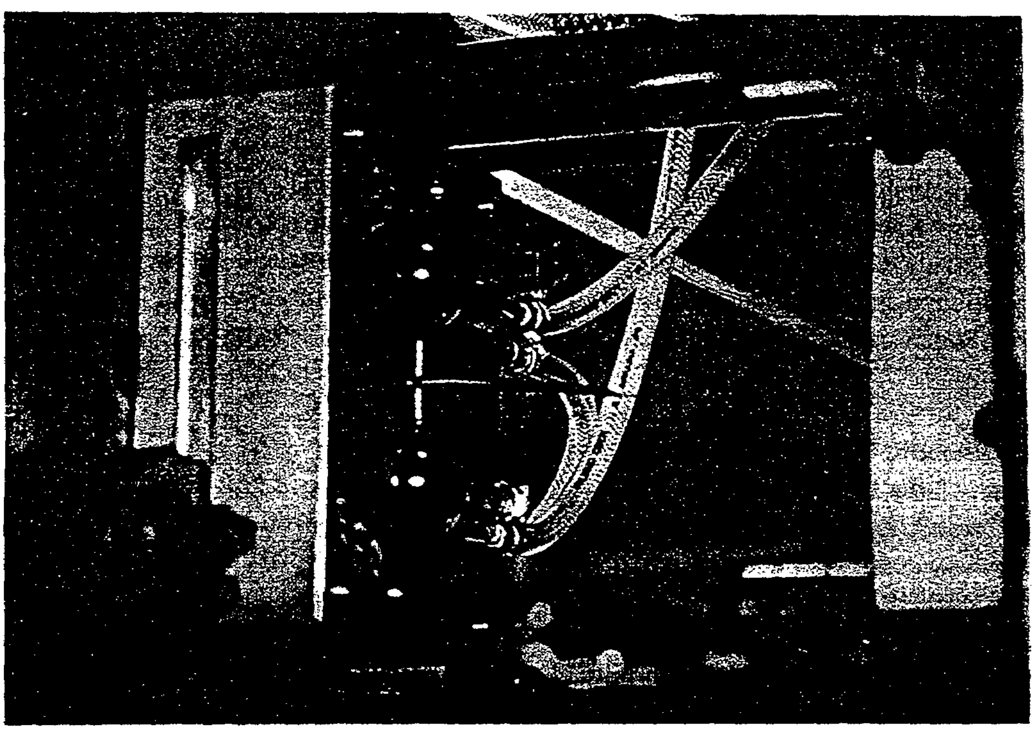


Figure 16. The injection mould

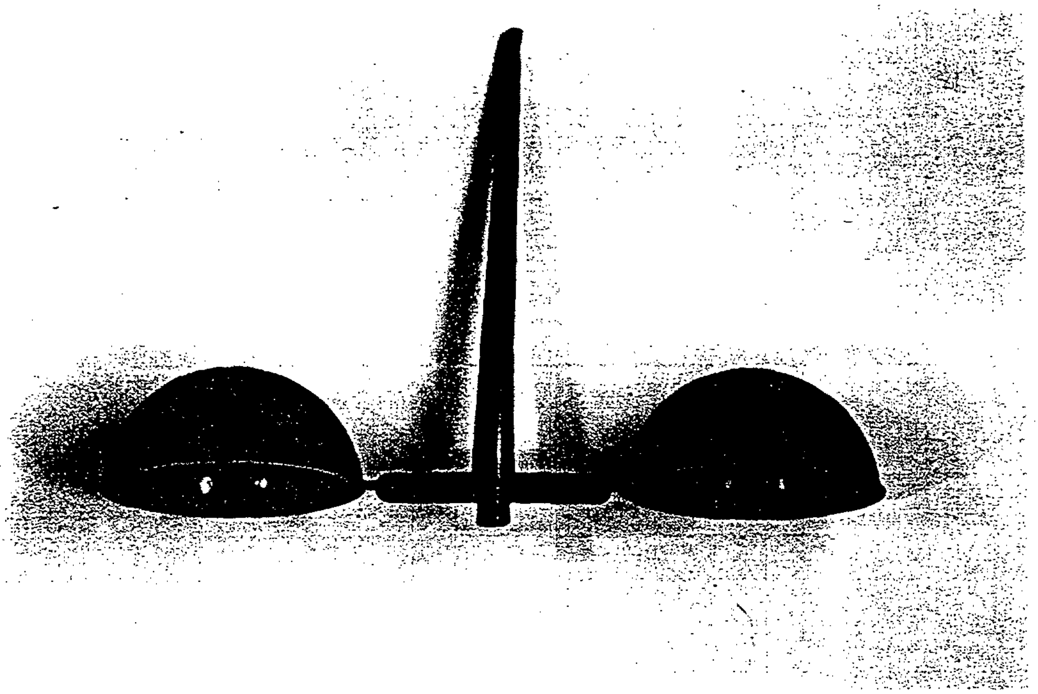


Figure 17. Plastic par% produced with the mould

CONCLUSIONS

Process Modelling

The validation of the finite element code developed for the prediction of the part distortions during SLA processes has shown a good agreement with experimental measurements. This agreement shows that this code can be used bye the users of SLA equipments to help in taking decisions about which building parameters (layer thickness, type of resin, orientation of the part in the platform, etc.) should be used in order to minimize the part distortions.

The finite element code for the analysis of SLS processes has shown to be very powerful in the prediction of many different characteristics of a single sintered track under a specific set of sintering parameters. Predicted values of layer thickness, temperature distribution, density distribution, internal residual stresses and final geometry of a track can be obtained.

The influence of tha laser power intensity and the laser scanning velocity in the characteristics of the final sintered track have been studied using the finite element code. This study has shown the possibilities of this code for the optimisation of the laser sintering parameters.

Process Engineering

Using the high power CO_2 laser working areas of process parameters were found out to get laser sintered tracks with sufficient green strength and no cracks. These results correspond well to that using the laser sintering laboratory equipment.

Cracks and curl formation are the main problems in laser sintering of metallic powders. Cracks occur when particle bond generated by laser sintering is too weak or brittle, for example because of inter-metallic compounds in copper-tin powders. Lead supplies a ductile particle bond, and does not build intermetallic compounds with copper. But the volume shrinkage of the powder materials causes curl formation which can also terminate the process. On the other hand volume shrinkage in copper-lead powders depends strongly on process parameters and was minimized but not negligible by parameter optimization.

Part fabrication of copper-lead **(40 vol.'%)** powder was possible at limited number of layers (≤ 25), The probability of delamination faults due to too weak interlayer bond rises at increasing layer number. The main reason for the statistical appearance of delamination is supposed to be the insufficient accuracy of the z-axis.

The addition of polymer binder to the metal and ceramic powders enhances their feasibility for laser sintering processes. Not only curl formation disappears, but also the green strength is considerably increased. The polymer is responsible for process stability to guarantee reproducibility. The accuracy of laser sintered parts is in x- and y-direction about ±0. I mm and in z-direction less than 0.3 mm. The relative density of green parts ranges 50 to 70 % while the roughness is 60 pm. The copper parts could be debindered without losing their geometrical shapes. Using metal or ceramic powders mixed with a polymer binder, functional and technical prototypes can be produced via process chains presented in Figure 12.

Investigations of three dimensional temperature distributions prove the increased thermal conductivity of laser sintered areas for copper-lead powders. The surface temperature was measured in the range of 450 to 550"C. The 350°C isotherm might reach 0.9 mm. The measurements reveal also temperature maintaining time and maximum temperatures depending on the depth beneath powder surface. Furthermore, closed loop process controlling was realized to keep the powder surface temperature at 800 °C constantly.

Because of shortcomings in the existing. equipments a new process chamber was designed containing automated powder recoating system, accurate z-axis, closed loop controlled preheating and shielding gas supplies. This chamber is built at the time.

Tooling Engineering

The aim of the research carried out in the tooling engineering area concentrates mainly on the study of the possibilities that RP technologies offer for fast prototype mould production for the manufacture of small preproduction runs of pieces or the fine tuning of technological processes.

During the first part of this work it reached the conviction that the progress of selective laser sintering (SLS) is being hindered by the objective difficulties raised in attempting to enlarge the working chamber, and to sinter materials other than thermoplastic resins. Therefore, these difficulties mean that SLS will be regarded as a marginal technique confined to applications where the dimensions are small and the part required can be made by investment casting. Attention was concentrated also to other RP techniques.

At the end of the first half of the research activity it was possible to affirm that:SLA and SLS offer the best precision. SLS shows a better stability over the time, but SLA gives abetter surface finish, bigger working area (till1000x500 mm) and moreover it is less expensive and more diffuse.

The SLA was used to produce a female model and a male model sized down to allow for the thickness of the part to be produced. Two techniques are employed to produce the metallic replicas: metal plating and thermal spraying. The thickness of the shell was in both cases of about 5mm. A mould was designed with two equal patter with metal inserts obtained applying the two mentioned techniques. Each pattern was made by the steel cylindrical body and the metal replicas connected to the steel body using an epoxy resin. The epoxy resin was charged with metallic prticles in order to improve theral conductivity. The test has shown that the two pattern are able to produce more than a few hundred parts.

As a conclusion of this area it can be said that the proposed technology is suitable to be improved in order to be industrially employed to produce fictional prototypes.

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