

# A Framework for Developing a Hybrid Investment Casting Process

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**Abstract** - Traditionally, the process of investment casting is used for making complex components. But, investment casting is considered economical only when the production volume is high enough. If only limited numbers of pieces are promptly required such as in making prototypes, design iterations and design optimisations the investment casting process proves to be very costly due to time and tooling cost for making dies for producing wax patterns. In such situations, the rapid prototyping technologies are considered very useful as these can produce the patterns with good accuracy and without the necessity of costly hard tooling. The fused deposition modeling (FDM) is one of the rapid prototyping technology that can use plastic material, which can be effectively used for making patterns for investment casting. This combination of the traditional investment casting process with the modern rapid prototyping technologies to obtain a new process may be termed as hybrid investment casting. This study is intended to develop a framework for developing a hybrid investment casting process for industrial applications. For this newly developed process, various process parameters, their control and effects have been represented to obtain the desirable mechanical and metallurgical properties of the castings.

**Keywords:** Fused Deposition Modeling, Hybrid investment casting, Mechanical properties, Metallurgical properties

## I. INTRODUCTION

Investment casting (IC) is considered a feasible solution when components have complex features such as thin walls, undercut contours and inaccessible spaces which are difficult or impossible to produce using other fabrication methods [1]. But, this process requires a wax pattern which is made by using costly dies. Therefore, if the required production volume is too low such as in prototyping, design iterations, custom implants and satellite parts etc. the die making for IC is considered costly and time consuming. This costly tooling

can be completely eliminated by using rapid prototyping (RP) technologies, thus making the IC viable for low and very low volume projects [2]. RP is an additive process in which paper, wax, plastic or other materials are combined layer by layer to create a solid object. The direct and indirect use of RP technologies in IC has been discussed by many researchers [3-6] but very less work has been done on the hybridisation of FDM and IC to achieve the desired accuracy, surface finish and cooling rate for the castings.

In the present study the traditional IC process is combined with the modern RP technologies to obtain a new process termed as hybrid investment casting (HIC). For this purpose the fused deposition modeling (FDM) method of RP technologies has been selected. The FDM is a RP technology that can be successfully used to make 3D models by using plastic material. These 3D plastic models can be used as patterns in IC process. This study explores the step by step procedure along with figures, to develop an HIC process. The various process parameters that will affect the mechanical and metallurgical properties of casted parts have also been discussed. The methods for the control of these parameters have also been revealed.

## II. OVERVIEW OF THE FDM PROCESS

The FDM process is a solid-based RP method that constructs three-dimensional objects directly from 3D CAD data. Different wax materials and non-wax materials like ABS, elastomer, polycarbonate and poly-phenol sulphone are available which can be used on FDM for making patterns and can be burnt easily during autoclaving/firing. Fig-1 represents the schematic diagram for FDM process. The basic equipments of FDM machine involve drive wheels (to drive the material filament from its cartridge into heater), a heater and liquefier (to melt the filament), a tip (nozzle that remove/extrude out the filament), a platform (the base where

the filament is deposited), and a piston (to move the platform at z axis). There is a second extrusion nozzle for the support material (different from the model material).

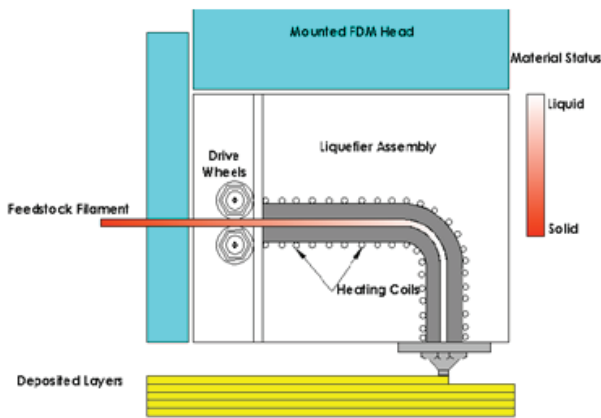


Fig. 1 The schematic diagram for FDM process [7]

The material is supplied in the from a roll of plastic filament on a spool. The filament is extruded in a semi-molten state and in a thin ribbon form. The thin ribbon shapes also confirm the bonds of filaments at each layer [8]. An FDM machine has been shown in Fig-2.



Fig.2 3D view of an FDM machine [9]

### III. METHODOLOGY FOR HIC PROCESS

In HIC process a three dimensional CAD model of the component to be produced, is required. Therefore, after selecting the component a 3D CAD model is prepared by using any CAD software. This 3D CAD model is saved as STL file format. The STL format file is required to work with FDM machine. This STL file is given as an input to the FDM machine. The FDM machine processes this file to cut it into thin layers and generate tool paths. A control file is

generated according to the various settings of the machine like material selection, layer thickness, type of support, model interior, STL units and scale etc. The FDM machine uses two materials i) build material ii) support material. The support material is used to build the support structures that are automatically generated for overhanging geometries and are later removed by breaking them away or by ultrasonic cleaning. After removal of the support structure the pattern is ready to use (with some optional post processing) for IC. The various steps of the methodology for developing the HIC process is given in Fig-3.

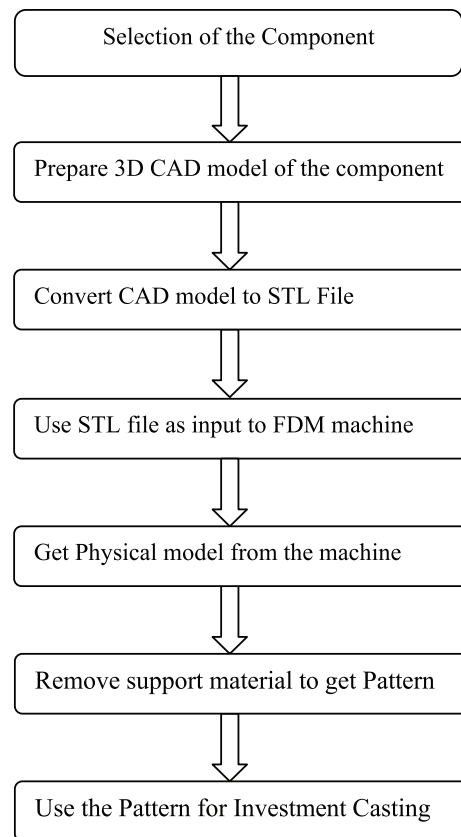


Fig. 3 Steps for developing HIC process

In HIC the output of the process depends upon a number of input factors. These factors influence the surface finish, dimensional accuracy, hardness and microstructure of the end product. The surface finish and dimensional accuracy are vital in moulding and parts assembly. The mould duplicates whatever kind of surface condition and accuracy the master pattern presents. Therefore, the master pattern made by FDM must have good surface finish and dimensional accuracy. The developing of HIC along with main process parameters and their control has been discussed below.

## IV. STEPS FOR FRAMEWORK FOR HIC PROCESS

### A. Selection of Component

The first step is the selection of the component which is required to produce by using HIC process. Any type of complex or simple geometry can be produced by this process. However, there is a limitation on the maximum size of the component on the basis of the type of FDM machine used. The machines are available that are capable to produce a model up to size of 1000X800X500 mm. However if the components have larger size than the maximum allowable dimensions of the machine, the components can be prepared in parts and then can be successfully joined afterwards with the help of liquid adhesives. For the sake of an example, in this study a part known as 'stem' has been selected. This part is used by the surgeons for total hip replacement joint in medical field.

### B. Preparing 3D CAD model of the Component

After selecting the component a 3D CAD model is required. This model can be made in any drawing software like Solidworks, ProE, Unigraphics etc. The pouring basin, sprue, ingates, runners and risers are also become the part of 3D CAD model. However as discussed above, these can be made in a separate drawing and then can be joined to the main part with the help of adhesive. The 3D CAD drawing of the selected part has been shown in Fig.4.

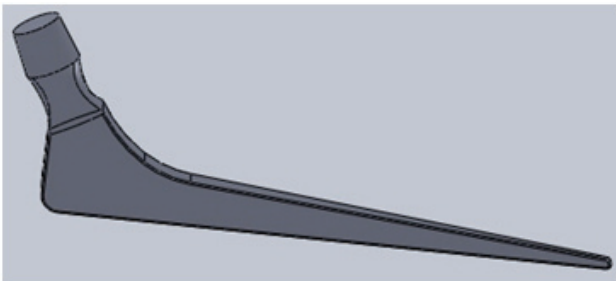


Fig. 4 3D CAD model of the selected component

### C. Converting CAD Model to STL File

The STL file translate the part geometry from a CAD system to the RP machine. The STL format consists of a web of triangles to represent the whole model. These triangular surfaces are used to express the real surfaces of the part. The STL file of the selected component has been shown in Fig.5.

All curved surfaces on 3D CAD model are approximated as a series of linear segments in STL file, leading to a non-smooth surface of a part. The CAD model can have smooth

curved surfaces but the RP process must have the model broken into discrete volumes to build the part. To have a continuous smooth curved surface the volume of each discrete piece would have to be infinitesimal small. But the larger the pieces the fewer are needed to approximate the part. However, fewer pieces would lead to less accurate approximation when compared to the original model.

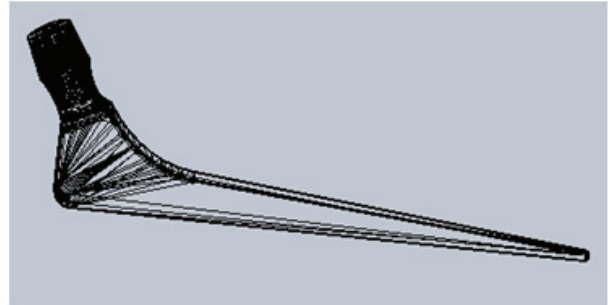


Fig. 5 STL file of the selected component

There are two ways for user to control tolerance and accuracy of the triangles in STL file. The user can adjust the maximum acceptable angle between the model lines and the tangent of the original curve. The user can also input the maximum acceptable distance (known as deviation in Solidworks) between the model line and the original curve. It should be noted that putting smaller value for the angle and deviation by the user, the closer the model line be to the original curve. It means more number of triangles mean more smooth and accurate surface. However, for large models very small and large number of triangles would lead to very large and unmanageable size of the STL file. Therefore, a trade-off has to made between file size and accuracy. Various angle and deviation options like coarse, fine and custom are available when STL file is generated from CAD software. As a rule of thumb triangles of the sizes between 0.02 mm and 0.05 mm will produce a good STL file [8]. The angle can be set in between 0.5° to 10° for good results.

### D. Using STL file as input to FDM machine

The STL file generated is supplied as an input to the FDM machine. But different setting options are available on FDM machine. These settings would affect the dimensional accuracy and surface finish of the output parts. These parameter settings and their effects have been discussed below:

**Orientation of the STL Part**

Orientation of the part means selecting the build direction. Often, a surface of the largest area of a part is chosen as the bottom surface and the part is then build along z-direction. The orientation at which the part is built, can have a significant effect on the quality of various surfaces of the part. The different orientations have different errors and different number of layers requirements. The orientation of the part also affects other factors such as the build time, the complexity of the support structure, shrinkage, curling and trapped volume.

The common surface error due to poor orientation is staircase error which is caused by the layer by layer nature of the RP building process. Inclined and curved surfaces show staircase effects more predominantly than other surfaces. The staircase effect cannot be completely eliminated. However, the effect can be reduced by decreasing the layer thickness and by suitably orienting the part so that the effect of overall staircase error is greatly reduced. It should be noted that the staircase effect will reduce the surface finish in the z-direction. Therefore suitable orientation and positioning can be decided on the basis of the functional and non-functional dimensions on different sides of the model. Two different typical orientations of the selected part has been shown in Fig-6a and Fig-6b.

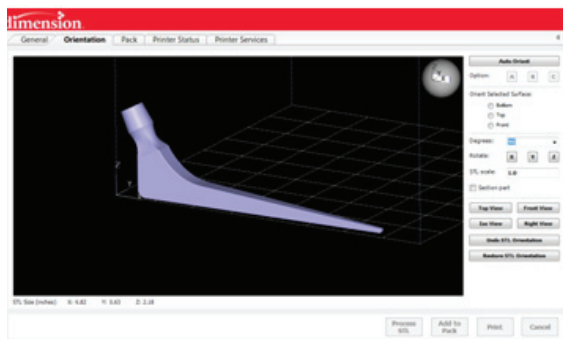


Fig. 6a A typical orientation of the selected part

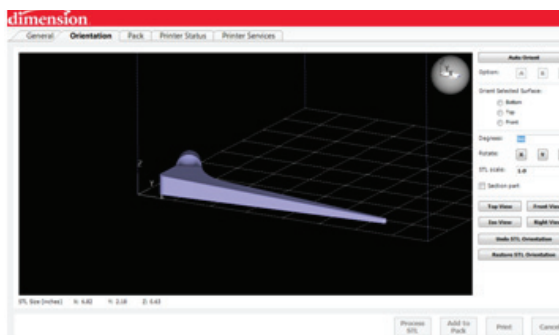


Fig. 6b Another typical orientation of the same part

**Layer Thickness**

In FDM layer upon layer is deposited to build the model. Many researchers has found that the layer thickness significantly influence the surface finish. Many researchers have proved that layer thickness is the most influencing parameter for the surface finish of layer manufacturing processes [10-11]. In general, a thinner slice layer will produce better surface finish by reducing the stair case effect but it will increase the build time. A typical layer thickness for an FDM machine may be 0.0070 mm or higher. Therefore, if the FDM machine supports different layer thicknesses then thin layer should be chosen for better accuracy and surface finish.

**Pattern Interior**

The outer profile of the model generated is very important as it will come in contact with the slurry for making the shape of mould cavity. However, the internal portion of the pattern may be made hollow by creating a tool path with larger air gaps in the middle that forms a mesh like interior of build material. For this purpose the different machines have different setting options. For example the Stratasys uPrint FDM machine have options for model interior as Solid, Sparse-Low density and Sparse-high Density. The Sparse-Low density should be selected for making IC patterns. This will reduce the material required and build time. Some typical settings have been represented through a part of a screen shot in Fig-7.

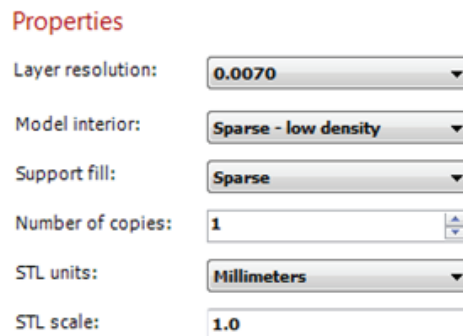


Fig. 7 Typical FDM machine settings

Another major problem which will be solved by the hollow patterns is the problem of cracking of ceramic shells during autoclaving. Most RP materials have coefficient of thermal expansion values that are larger than the ceramic material and as such, the expansion of the pattern during heating imposes significant amounts of stress on the ceramic shell [12].The hollow pattern would soften at lower temperatures

and collapse inwards before reaching the critical stress levels in the outer slurry shell. In addition to this, the Sparse-low density interior of the model will help to reduce the residual ash in the mould after burning the pattern. The residual ash can cause defects in the final castings.

**E. Getting Physical Model from the Machine**

After setting all the input parameters the FDM machine is run to get the desired model according to the drawing. The machine produces the final part without any intermediate setting or inspection. A drawing of the physical model of the stem before removing the support material has been shown in Fig.8. The support material layers can be seen at the base of the model as this model has been prepared by using the orientation shown in Fig.6a.



Fig. 8 Physical model with support material

**F. Removing Support Material from the Model**

The support material can be removed manually with the help of a nose pliers. However, if the support material is inside a cavity then ultrasonic cleaning is used for removing the support material. In ultrasonic cleaning the support material dissolves in an alkali liquid chemical having pH value 10. An image of ultrasonic cleaning machine is shown in Fig.9.



Fig. 9 Ultrasonic cleaning machine

After ultrasonic cleaning the model is washed with water. This model is now ready to use for investment casting or optional post processing for improving the surface finish. The

physical model produced by the machine after removing the support material is as shown in Fig.10.



Fig. 10 Physical model without support material

**Post Processing**

In FDM, the surface finish of the parts is found to be inferior to some other RP technologies due to the resolution of the process which is dictated by the filament thickness. Therefore post processing of the patterns may be required before using them for IC. The common and easy methods to increase the surface finish are using sand paper and thin coating of wax. Chemical dipping can also be used to increase the surface finish [13]. The Stratasys Inc. has developed a vapour smoothing process to smoothen the ABS parts to a finish similar to injection moulded parts. This method can reduce the surface roughness from Ra 600 to Ra 40-Ra 60 equating to a 10 to 15 times smoother surface [14].

**G. Using Model as Pattern in IC**

The model is now ready to use as pattern for IC. For this purpose the model is attached with the ingates of the tree (if pouring basin, sprue, gates and runners are produces separate) as shown in Fig-11. This tree is also made by using FDM machine in the similar way to that of making a component.

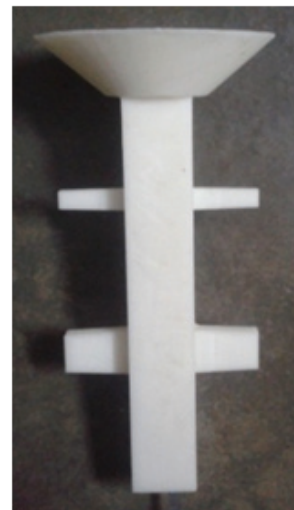


Fig. 11 Pouring basin, sprue, runners and gates

After fixing the pattern to the tree, the slurry layers are deposited similar to wax pattern tree in conventional IC. In conventional method the wax pattern is removed by autoclaving. But in HIC the plastic patterns are removed by burning the patterns inside a furnace at higher temperature typically near to 850°C. The temperature is further increased up to 1050°C for baking the slurry shell. The molten metal is then poured into the shell to get the desired shape of casting. The casting of the selected component is shown in Fig.12.

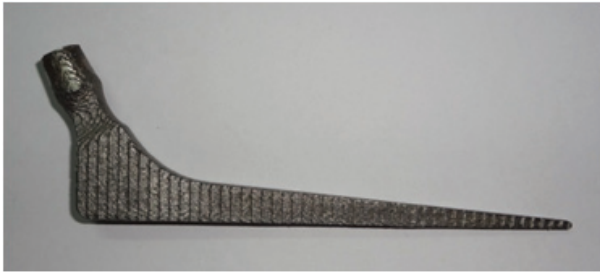


Fig. 12 Metal Part Produced by HIC

This piece has been produced without any post processing therefore surface irregularities can be seen on the surface which are more predominant on taper surfaces.

#### V. CONTROLLING METALLURGICAL PROPERTIES

The metallurgical properties of the casting can be controlled by controlling the cooling rate of the casting. Apart from the composition, the cooling rate is the second biggest contributor to decide the mechanical and metallurgical properties of the castings. The dendrite arm spacing in a given alloy is depend strongly, and solely, on cooling rate and do not vary very much from alloy to alloy. The mechanical and other properties of a variety of cast alloys also depend strongly on dendrite arm spacing [15].

Besides applying external cooling sinks there are some methods to increase the cooling rate in IC. The rate of cooling can be increased by reducing the number of slurry layers on the pattern. However, by using this method the rate of cooling can be increased only up to some extent as the ceramic shell should remain sufficiently strong to bear the weight and pressure of the molten metal. The number of layers can be varied according to the size of the product.

In another method, Nicolas Chvorinov has given an equation that relates the solidification time for a simple casting to the volume and surface area of the casting. In simple terms, the rule establishes that the casting with large surface area and small volume will cool more rapidly

than a casting with small surface area and a large volume. The relationship can be written as

$$t = B \left( \frac{V}{A} \right)^n$$

Where

$t$  is the solidification time,

$V$  is the volume of the casting,

$A$  is the surface area of the casting that contacts the mould,

$n$  is a constant (usually 2),

and  $B$  is the mould constant in min/cm<sup>2</sup>

The mould constant  $B$ , can be calculated using the following equation [16].

$$B = \left[ \frac{\rho_m L}{(T_m - T_o)} \right]^2 \left[ \frac{\pi}{4k\rho c} \right] \left[ 1 + \left( \frac{c_m \Delta T_s}{L} \right)^2 \right]$$

Where

$T_m$  = melting temperature of the metal (in Kelvin)

$T_o$  = initial temperature of the mould (in Kelvin)

$\Delta T_s = T_{pour} - T_m$  = superheat (in Kelvin)

$L$  = latent heat of fusion (in [J.Kg<sup>-1</sup>])

$k$  = thermal conductivity of the mold (in [W.m<sup>-1</sup>.K<sup>-1</sup>])

$\rho$  = density of the mould (in [Kg.m<sup>-3</sup>])

$c$  = specific heat of the mould (in [J.Kg<sup>-1</sup>.k<sup>-1</sup>])

$\rho_m$  = density of the metal (in [Kg.m<sup>-3</sup>])

$c_m$  = specific heat of the metal (in [J.Kg<sup>-1</sup>.k<sup>-1</sup>])

Some factors in this equation can be controlled to control the cooling rate. The mould constant depends on the properties of the metal, such as density, heat capacity, heat of fusion and superheat, and the mould, such as initial temperature, density, thermal conductivity, heat capacity and wall thickness.

#### VI. CONCLUSIONS

In the present work a framework for development of HIC has been proposed. For hybridization, the plastic pattern based upon FDM process was used and final investment casting for a biomedical application has been highlighted. The results of study suggest that this hybridization is possible for various industrial and biomedical components. The tailor made results as regards to mechanical and metallurgical properties can be obtained.

## ACKNOWLEDGEMENTS

The authors thankfully acknowledge the research grant from UGC, New Delhi (India) under UGC Minor Research Project Scheme to carry out the research work, titled “Investigations on Producing Cost Effective Rapid Investment Casting Using Rapid Prototyping Technology”.

## REFERENCES

- [1] Kumar, P., Ahuja, I.P.S. and Singh, R.(2012) ‘Application of Fusion Deposition Modelling For Rapid Investment Casting - A Review’, *International Journal of Materials Engineering Innovation*, Vol. 3, No. 3/4, pp. 204-227.
- [2] Rosochowski, A. and Matuszak, A. (2000) ‘Rapid tooling: the state of the art’, *Journal of Materials Processing Technology*, Vol. 106, No. 1-3, pp.191-198.
- [3] Lee, C.W., Chua, C.K., Cheah, C.M., Tan, L.H. and Feng, C. (2004) ‘Rapid investment casting: direct and indirect approaches via fused deposition modelling’, *The International Journal of Advanced Manufacturing Technology*, Vol. 23, No. 1-2, pp. 93-101.
- [4] Chua, C.K., Feng, C., Lee, C.W. and Ang, G.Q. (2005) ‘Rapid investment casting: direct and indirect approaches via model maker II’, *The International Journal of Advanced Manufacturing Technology*, Vol. 25, No. 1, pp. 26-32.
- [5] Cheah, C.M., Chua, C.K., Lee, C.W., Feng, C. and Totong, K. (2005) ‘Rapid prototyping and tooling techniques: a review of applications for rapid investment casting’, *The International Journal of Advanced Manufacturing Technology*, Vol. 25, No. 3-4, pp. 308-320.
- [6] Safaeian, D. and Vaezi, M. (2009) ‘Investment casting of gas turbine blade by used of rapid technologies’, *Australian Journal of Basic and Applied Sciences*, Vol. 3, No. 3, pp. 2979-2988.
- [7] Nikzad, M., Masood, S.H. and Sbarski, I. (2011), “Thermo-mechanical Properties of a Highly Filled Polymeric Composites for Fused Deposition Modelling”, Vol. 32, No. 6, pp. 3448-3456.
- [8] Liou, F.W. (2008) *Rapid Prototyping and Engineering Applications, a Toolbox for Prototype Development*, CRC Press, Taylor & Francis Group, London.
- [9] Singh R. and Garg H.K. (2011), *Pattern development for hand tool die with fused deposition modeling*, Lambert Academic Publishing AG & Co. KG, Saarbrücken, Germany, ISBN-NR: 978-3-8433-8735-4.
- [10] Anitha, R., Arunachalam, S. and Radhakrishnan P. (2001) ‘Critical parameters influencing the quality of prototypes in fused deposition modeling’, *Journal of Materials Processing Technology*, Vol. 118, No. 1-3, pp. 385-388.
- [11] Ahn, D., Kweon, J.H., Kwon, S., Song, J. and Lee, S. (2009) ‘Representation of surface roughness in fused deposition modeling’, *Journal of Materials Processing Technology*, Vol. 209, No. 15-16, pp. 5593-5600.
- [12] Yao, W.L. and Leu, M.C. (1999) ‘Analysis of shell cracking in investment casting with laser stereolithography patterns’, *Rapid Prototyping Journal*, Vol. 5, No. 1, pp. 12-20.
- [13] Galantucci, L.M., Lavecchia, F. and Percoco, G. (2010) ‘Experimental study aiming to enhance the surface finish of fused deposition modeled parts’, *CIRP Annals- Manufacturing Technology*, Vol. 58, No. 1, pp. 189-192.
- [14] [http://www.stratasys.com/~media/Main/Secure/System\\_Spec\\_Sheets-SS/Fortus-Product-Specs/Fortus-SS-FinishingTouchSmoothingStation-01-13-web.ashx](http://www.stratasys.com/~media/Main/Secure/System_Spec_Sheets-SS/Fortus-Product-Specs/Fortus-SS-FinishingTouchSmoothingStation-01-13-web.ashx) [Accessed on 10.07.2013]
- [15] Flemings, M.C. (1974) ‘Solidification Process’, *Metallurgical Transactions*, Vol. 5, pp. 2134.
- [16] Askeland, Donald R., and Phule, Pradeep P. (2004) *Essentials of Materials Science and Engineering*, Thomson, Ontario, Canada.